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Water Use in Global Livestock Production—Opportunities and Constraints for Increasing Water Productivity

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Abstract Increasing population, change in consumption habits, and climate change will likely increase the competition for freshwater resources in the future. Exploring ways to improve water productivity especially in food and livestock systems is important for tackling the future water challenge. Here we combine detailed data on feed use and livestock production with Food and Agriculture Organization of the United Nations (FAO) statistics and process-based crop-water model simulations to comprehensively assess water use and water productivity in the global livestock sector. We estimate that, annually, 4,387 km³ of blue and green water is used for the production of livestock feed, equaling about 41% of total agricultural water use. Livestock water productivity (LWP; protein produced per m³ of water) differs by several orders of magnitude between livestock types, regions, and production systems, indicating a large potential for improvements. For pigs and broilers, we identify large opportunities to increase LWP by increasing both feed water productivity (FWP; feed produced per m³ of water) and feed use efficiency (FUE; protein produced per kg of feed) through better crop and livestock management. Even larger opportunities to increase FUE exist for ruminants, while the overall potential to increase their FWP is low. Substantial improvements of FUE can be achieved for ruminants by supplementation with feed crops, but the lower FWP of these feed crops compared to grazed biomass limits possible overall improvements of LWP. Therefore, LWP of ruminants, unlike for pigs and poultry, does not always benefit from a trend toward intensification, as this is often accompanied by increasing crop supplementation.

1. Introduction

Driven by increasing global population and rising per capita food demand, global production of animal source foods (ASF) has more than tripled over the last 50 years, accompanied by a threefold increase of crops used for animal feed (Food and Agriculture Organization of the United Nations [FAO], 2018). One third of all cropland is now being used to produce feed crops (Steinfeld et al., 2006), and one quarter of the ice-free land area of the world is occupied by pastures (FAO, 2018). Continued population growth and an unbroken trend toward more meat and dairy-intensive diets will put enormous pressure on the food system in the coming decades (Alexandratos & Bruinsma, 2012; Bodirsky et al., 2015). In total, global agricultural output will have to increase by 70–110% by 2050. The major part of both the production and consumption of animal products is expected to take place in developing countries (Alexandratos & Bruinsma, 2012; Godfray et al., 2010).

Already today, more than 2 billion people live in countries where total freshwater withdrawals exceed 25% of the total renewable freshwater resource (United Nations, 2017). Population growth and climate change are both projected to substantially increase water scarcity for large portions of humanity (Heinke et al., 2019). Water is one of the most basic resources needed in agricultural production, and agriculture is the single largest water user accounting for 69% of global freshwater withdrawals (FAO, 2016) and an even higher share of consumptive freshwater use. In addition to this "blue water," agriculture consumes many times more "green water," i.e., soil moisture from naturally infiltrated rainfall on both irrigated and rainfed agriculture land (Rost et al., 2008). In view of rising food demand, it is imperative to limit further increase in agricultural water demand by seeking ways to produce more per unit of water.

Previous studies have estimated consumptive water use (CWU) by the livestock sector as a whole (De Fraiture et al., 2007; Mekonnen & Hoekstra, 2012; Weindl et al., 2017) and for different ASF in different countries (Mekonnen & Hoekstra, 2012). The vast majority of the CWU by the livestock sector is related to the production of feed, whereas only about 2% of it is water for drinking and servicing (Mekonnen & Hoekstra, 2012). Thus, the estimation of the feed amounts from different sources required to produce ASF and the water use associated with the production of this feed are central to the estimation of CWU for livestock production. We here use a comprehensive data set from Herrero et al. (2013), which provides estimates of production of ASF and corresponding use of feed from different sources. The data set is based on a mechanistic digestion and metabolism model (Herrero et al., 2008) to provide biologically plausible estimates and is harmonized to the FAO Statistical Database (FAOSTAT) to match reported use of crops for feed (concentrate feed) and production of ASF around the year 2000. The state-of-the-art dynamic global vegetation, hydrology, and crop model LPJmL4 (Schaphoff, von Bloh, et al., 2018) is used to estimate the water required to produce feed crops, cultivated forages, and grazed grass. Unlike previous studies that have only accounted for the direct water use, i.e., the evapotranspiration (ET) occurring during the growing period, we also include the ET that occurs from fallow cropland outside the growing period as an indirect water use in our estimates of CWU of feed and ASF. Accounting for the indirect fallow water use is particularly important when comparing annual and perennial crops, in which the former would be unjustifiably favored when only growing period ET were used.

The goal of this study is twofold. First, we aim to provide revised estimates of CWU in global agriculture, i.e., how much of it is attributable to the livestock sector and to the different ASF in different regions and production systems. Second, we analyze how variations in livestock water productivity (LWP; defined as g protein produced per m^3 of CWU) are caused by variations in feed water productivity (FWP; defined as kg feed produced per m^3 of CWU) and variations feed use efficiency (FUE; defined as g protein produced per kg of feed) and assess the possible implications for the potential to improve LWP.

2. Materials and Methods

Estimation of livestock water use and water productivity (WP) requires information about feed use by livestock, the amount of protein produced from the feed, and the water used for producing the feed. Feed use and production in the global livestock sector are based on data from Herrero et al. (2013), which provide detailed information for 919 different combinations of livestock production type, production system, and world regions, hereafter referred to as livestock production units. Livestock production types differ by animal species, use of feed types, and produced ASF types (Table S1 in the supporting information). For each of the two ruminant types "bovines" and "sheep and goats," a "meat" sub-type and a "diary" sub-type are distinguished, which produce only meat or both milk and meat, respectively. Each of the four types can occur in up to eight ruminant production systems (Robinson et al., 2011) in each of 29 world regions (see Figure S1 for a map of world regions). All ruminants rely on roughage (grazed biomass, crop residues, and cultivated forages) as a primary feed source with up to 50% supplementation of feed crops. The effect of feed composition and nutritional quality on FUE is explicitly accounted for by applying a mechanistic digestion and metabolism model (Herrero et al., 2013).

Monogastric animals analyzed in this paper, poultry and pigs, are distributed over five livestock production types (Table S1). For poultry, meat-producing broilers and egg-producing layer hens are distinguished for industrial production, whereas smallholder production is assumed to produce both eggs and meat simultaneously (dual-purpose poultry). All poultry are fed with feed crops, but depending on the region, a significant part of the feed in smallholder production may come from alternative but unaccounted feed sources, such as scavenging and uneaten food (Herrero et al., 2013). Pigs in both industrial and smallholder production only produce meat and are fed with feed crops. However, like smallholder poultry, pigs in smallholder production also partially rely on unaccounted feed sources, which is why we treat them as a separate livestock production type. All livestock products are converted to edible protein using conversion coefficients given by Herrero et al. (2013). Total production, FEU, and LWP all refer to livestock production in terms of human-edible protein to acknowledge the importance of livestock products in human nutrition as a source of protein (Willett et al., 2019).

Green and blue water use for the production of the different feed components (feed crops, cultivated forages, grazed biomass, and crop residues) fed to animals in the 919 livestock production units is estimated from simulations with the dynamic global vegetation and hydrology model LPJmL4, which includes process-based representations of crop and grazing land dynamics (Schaphoff, von Bloh, et al., 2018; see Text S1 for details). Global production and related water use for 62 crops and crop groups are estimated using maps of harvested area and total cultivated area from MIRCA2000 (Portmann et al., 2010) and national yield statistics from FAOSTAT (FAO, 2018). Total production for all crops was estimated by multiplying harvested area with national yield from FAOSTAT. ET during the growing seasons of 18 major crops was estimated from LPJmL4 simulations by determining the management intensity for which simulated yield best matches yield from FAOSTAT at the country level. For all other crops, ET of generic annual and generic perennial crop types was used. ET from off-season and full-year fallow land was estimated assuming bare soil (black fallow) and assigned to crops based on harvested area and cropping intensity (see Text S2 for details). In addition to blue water consumption on the field, evaporation related to the transport of irrigation water to the field (conveyance losses) was estimated based on country-specific irrigation efficiencies (Jägermeyr et al., 2016), assuming that half of the losses are evaporative (Rost et al., 2008).

From the thus obtained estimates of CWU for harvested crops, we determine CWU related to crops and crop products utilized for food, feed, and other uses at the national level by using the information about trade and utilization given in the FAOSTAT Food Balance Sheets and Commodity Balances Sheets (FAO, 2018). Only net imports and exports are accounted for, and a global trade pool is assumed for each commodity. Water for commodity quantities reported as waste is proportionally distributed to food, feed, and other uses, resulting in a decrease in WP for actually utilized commodities (for further details, see Text S3).

Production of cultivated forage and related CWU was estimated using maps of harvested area from MIRCA2000, gridded yield estimates from Monfreda et al. (2008), and simulated ET from LPJmL4 (Text S2). The utilization of cultivated forage in each livestock production unit was estimated by adjusting the amounts of occasional feed use from Herrero et al. (2013) until they matched the estimated forage production in the corresponding ruminant productions systems (see Text S4 for details). The difference between occasional feed demand and estimated use of fodder grasses was added to the demand for grazed biomass.

For the estimation of CWU for grazed biomass, we performed a series of LPJmL4 simulations with a wide range of grazing intensities to determine the maximum biomass yield and corresponding ET (Text S1). To estimate potentially available biomass for grazing, yields were multiplied with the sum of grassland and woodland and barren and sparsely vegetated land from the Global Agro-Ecological Zones (GAEZ) land cover data set (Fischer et al., 2008). For India, 10% of built-up land was added to account for roadside grazing and grazing on small pasture patches within human settlements (Spate & Learmonth, 2017). Total grass demand on the production unit level was downscaled to the grid cell level using the spatial distribution of ruminants and ruminant production systems given by the Gridded Livestock of the World version 2 data set (Robinson et al., 2014). Inconsistencies in the downscaling of grass demand were resolved by redistributing excess demand within the respective ruminant production system and, if insufficient, within the respective region (see Text S5 for details). The CWU for the estimated grazing demand in each grid cell was estimated by multiplying with annual ET per kg of grazed grass determined for the maximum yield scenario. Finally, the area potentially available for grazing according to the GAEZ land cover data set and the definition above is reduced to match "land under permanent meadows and pastures" reported by FAOSTAT (FAO, 2018) in each country (see Text S5 for details). This procedure assigns only a fraction of grassland ET—equal to the ratio of actually grazed to potentially available biomass—to livestock CWU, thus accounting for the importance of other ecosystem services derived from grasslands. Although such an allocation rule that is solely based on biomass cannot account for the often complex relationship between grazing intensity and other grassland ecosystem services, it avoids all problems entailed with the valuation of ecosystem services (de Groot et al., 2012; Jacobs et al., 2014). The assumed increase of ecosystem services with decreasing grazing CWU (or vice versa) is intelligible and in line with other studies (Schyns et al., 2019; Weindl et al., 2017) but may not be valid under all circumstances (Petz et al., 2014).

No water use was allocated to crop residues (straws and stovers), thus assuming that their use for feed has no environmental or economic consequences. We acknowledge that this assumption is debatable, especially for agricultural production systems where biomass is scarce. But assessing the implications of residue use (and
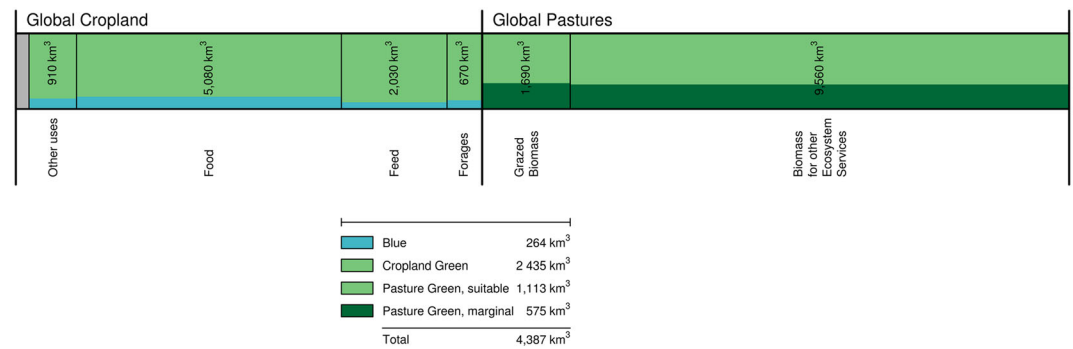
Figure 1. Total evapotranspiration (ET) from global agricultural lands, year 2000, divided into cultivated lands and pastures and differentiated into blue ET, green ET from cultivated lands, and green ET from pastures, differentiated as suitable for crop cultivation or marginal, i.e., not suitable. The bar is divided into six utilization categories. Total consumptive water use (CWU).

the water use allocated to it) would require comprehensive knowledge of many economic, environmental, and management aspects of agricultural production that are not available globally. Defining the value of residues based on market prices alone (e.g., Mathioudakis et al., 2017) cannot account for all these aspects, in particular, when data availability allows to only use a global representative price (see also Text S3 for a discussion about using prices to estimate value fractions).

3. Results and Discussions

3.1. Livestock Water Use From Global Agricultural Lands

In total, an annual water quantity of 20,191 km^3 is evaporated from global agricultural lands, with 7,670 km^3 green water and 1,269 km^3 blue water from cropland and 11,252 km^3 green water from pastures, averaged over the period 1998–2002 (Figure 1). In contrast to pastures, which are more or less permanently covered by grasses, a wide range of seasonal crops with short and long growing seasons are predominantly cultivated on cropland. Thus, most cropland is only temporarily covered by crops, so that only 4,564 km^3 of the total green ET from cropland occurs during growing periods and 3,105 km^3 during seasonal and annual fallow periods. Because fallow is part of the rotational use of cultivated lands, its ET is included in our analysis as an integral part of the CWU of crops. Annual blue water ET from fields during the growing period is 882 km^3, and no blue ET is assumed to occur from fallow assuming there is no irrigation in these periods. As the conveyance efficiency of irrigation infrastructure is low in many parts of the world (Rost et al., 2008), an additional 387 km^3 of blue water evaporates from open canals and temporary storages for the provision of irrigation water to the field.

In Figure 1 the annual ET from global agricultural lands is divided into CWU for six principal biomass utilization categories. About 5,078 km^3/yr of total cropland ET (57%) is attributed to the production of "food crops," 2,699 km^3/yr (30%) to the production of "feed crops" and "forages," and 910 km^3/yr (10%) to the production of biomass for "other uses," mainly fibers and biofuels. A small amount of 252 km^3/yr cropland ET (<3%) could not be allocated to one of these uses due to missing information on crop utilization in some countries (e.g., Papua New Guinea, Syrian Arab Republic, and Democratic Republic of the Congo). From pastures, 1,688 km^3/yr of annual ET (15%) is allocated to the production of "grazed biomass." The remaining ET from pastures is assumed to be associated with biomass which supports other functions of pastoral ecosystems, such as wildlife and carbon sequestration (Schyns et al., 2019). Overall, 10,627 km^3/yr of green and blue ET from global agricultural lands is associated with the production of biomass for human use as food, animal feed, fiber, and biofuels.

In total, the global livestock sector annually appropriates 4,387 km^3/yr of green and blue water for the production of feed crops, forages, and grazed biomass (Figure 1), equaling about 22% of the total ET from global agricultural land and 41% of total CWU for agricultural biomass for human use. Out of the annual total CWU in global livestock production, 4,123 km^3/yr (94%) is from green water, which is slightly less than
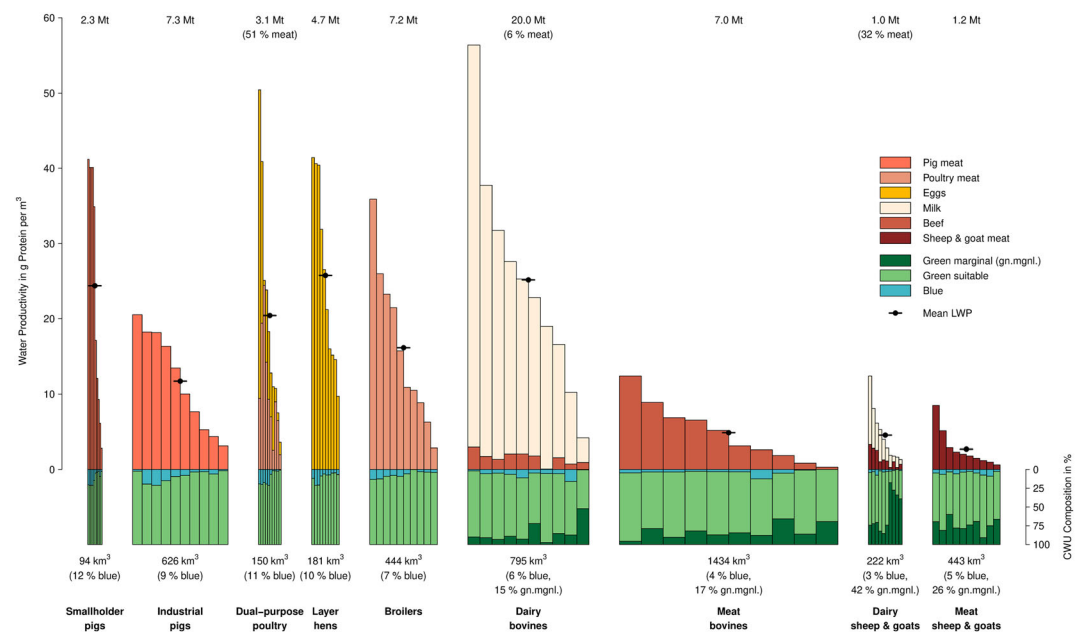
Figure 2. Consumptive water use (CWU) (km^3/yr), production of protein (Mt/yr), and water productivity (gP/m^3) for the global livestock sector, differentiated for nine livestock production types, three water sources, and three protein sources. The total CWU for each livestock type is divide into 10 equal portions, and the composition of CWU and the average water productivity are shown for each. The width of the bars depicting water productivity and composition of CWU is scaled so that the area covered corresponds to total production and CWU, respectively. Total production and CWU per livestock production type are also given on top and at the bottom, respectively. The dashed dot indicates average LWP for each livestock production type.

the 4,242 km^3/yr of green water used for food crops. However, more than one third of the green water used in livestock production is from pastures, which can be located on marginal lands where crop production is severely limited by environmental constraints (Ran et al., 2017; van Velthuizen et al., 2007). Hence, the green water from pastures on marginal lands is not directly comparable to the green water from cropland as it could not be used alternatively for crop production. Applying a "crop suitability index" (Fischer et al., 2008), we find that 575 km^3/yr (34%) out of the annual green CWU related to grazed biomass is from marginal pastures (crop suitability index < 0.1) and 1,113 km^3/yr from pastures is suitable for crop production. The proportion of ET from marginal pastures in total pasture ET is very similar (33%).

Only 6% of total CWU appropriated by the livestock sector for feed production is blue water, which is drastically less than the 16.5% and 14.1% of blue water in total CWU for food crops and other uses, respectively. This is not just the effect of the large contribution of green water from pastures (which are assumed to be entirely rainfed) but also the result of the smaller contribution of blue water to CWU for feed crops and forages on cropland (9.8%). Overall, only 264 km^3/yr of blue water is used for feed production, which is about one fifth of the 1,269 km^3/yr of total agricultural blue water consumption and less than one third of the 836 km^3/yr blue water used for food crops. However, additional blue water is required by the livestock sector for drinking and servicing. Globally, the evaporation from these blue water withdrawals amounts to 27 km^3/yr (Alcamo et al., 2003). This equals 10.2% of the blue CWU and 0.6% of total CWU for feed production.

3.2. Water Use for Livestock Types and Livestock Products

In total, the global livestock sector generates an annual human edible protein supply of 53.7 Mt (year 2000; Figure 2), with a global average LWP of 12.2 gP/m^3. About half of annual production (29.2 Mt) but almost two thirds of total annual livestock CWU (2,893 km^3) can be attributed to ruminants, and the remaining production (24.5 Mt) and CWU (1,494 km^3) are associated with monogastric animals. Thus, monogastric animals produce over 60% more protein per unit of total CWU than ruminants (16.4 gP/m^3 compared to 10.1 gP/m^3). However, the composition of CWU of ruminants and monogastric animals differs due to the fundamentally different composition of feed. Because the digestion system of ruminants is well suited to

digest cellulose feeds, the largest part of their global average feed mix (92%) consists of roughage, with grass from pastures making up the largest part (74% of roughage). As a result, most of the CWU of ruminants (58%) is green water from pastures, of which about one third is from marginal land. Monogastric animals, on the other hand, are only fed with concentrate feed (feed crops and animal by-products) so that CWU for this group only consists of green and blue water from cropland (Table S1). Although the share of blue water in CWU from cropland is larger for ruminants (11.0%) than for monogastric animals (8.8%), the share of blue in total CWU of ruminants is only 4.6% due to the large contribution of green water from pastures.

The division into nine livestock production types allows for a more in-depth analysis of water use and production. When assessing the relative importance for supplying human-edible proteins, the single largest contributor is the bovine dairy production providing 37.3%, followed by almost equally large protein supply from industrial pigs, 13.7%; industrial broiler, 13.4%; and meat bovines, 13.0%. The smallest protein contributions come from the sheep and goat production, with 1.9% from the dairy category and 2.2% from the meat type. The appropriation of CWU by livestock production types is different from their contribution to production, with meat bovines being the single largest water user with 32.7% of total livestock CWU, followed by dairy bovines with 18.1% and industrial pigs with 14.3%; smallest quantities are appropriated by layer hens, 4.1%; smallholder dual-purpose poultry, 3.4%; and smallholder pigs, 2.1%. The share of blue water in total CWU for monogastric animals varies from 6.8% for industrial broilers to 12.1% for smallholder pigs. These differences are the result of the geographical distribution of production, i.e., how much of production happens in regions with a high share of irrigation on cropland. Among ruminants, a comparatively high share of blue water is found for dairy bovines, which is mainly caused by the high share of cultivated feed crops and forages in the feed mix (21.5% compared to 14.6% average for remaining ruminants). The share of green CWU from marginal pastures differs by a factor of almost 3 among ruminant production types, which is mainly the result not only of differences in the share of green marginal water in grazing CWU (27.5% for meat bovines to 58.4% for dairy sheep and goats) but also of the contribution of grazing to the overall feed mix (60.4% for dairy bovines to 76.0% for dairy sheep and goats).

The different patterns of CWU attribution and contribution to production by the nine livestock production types translate into different LWPs. The highest average LWP is found for layer hens with 25.8 gP/m^3, followed by dairy bovines with 25.2 gP/m^3 and smallholder pigs with 24.4 gP/m^3. The lowest LWP is 2.7 gP/m^3 for meat sheep and goats (almost 10 times lower than that for layer hens or dairy bovines), followed by 4.5 gP/m^3 for dairy sheep and goats and 4.9 gP/m^3 for meat bovines. However, even larger LWP differences are found within livestock production types. In Figure 2, the total CWU appropriated by each of the nine production types is sorted from high to low LWP and divided into 10 equal CWU portions; for each portion, the composition of CWU and the amount and composition of protein produced from it is shown. The average LWP of the most and least efficiently used 10 % portion of CWU varies at least fivefold for layer hens and up to nearly 40-fold for meat bovines. As a result, the LWP ranges of the different livestock production types overlap, with low LWP found in each of the nine types.

3.3. Drivers for Variations in LWP

The huge differences in LWP (Figures 2 and S2) are the result of the wide range of conditions under which livestock rearing and feed production takes place. Many of these conditions are subject to crop and livestock management (fertilizer, pesticides, crop and livestock species, breeds, veterinary services) and can be improved to increase LWP. Other conditions, mainly environmental factors such as climate and soils, cannot be changed but may be addressed by management (e.g., by providing housing or shelter for animals). Due to incomplete knowledge about all different management factors that determine LWP in our analysis, it is not possible to fully quantify the "management gap," i.e., the difference between current and best management, and the corresponding productivity gap. In the following, we will instead analyze the contribution from variations in FWP (an aggregated measure of how efficiently water is used to produce the feed mix) and FEU (a measure of how efficiently the feed is used to produce meat, milk, and eggs) to variations in LWP and provide a qualitative assessment of the opportunities to improve LWP and the possible constraints and trade-offs.

In contrast to the previous section, where LWP was analyzed for the total volume of CWU, this section focusses on the differences in production conditions across regions and production systems. To facilitate an undistorted comparison of LWP, FWP, and FUE estimates, each production unit (one region for monogastric animals or one production system in a region for ruminants) is weighted equally, regardless of its
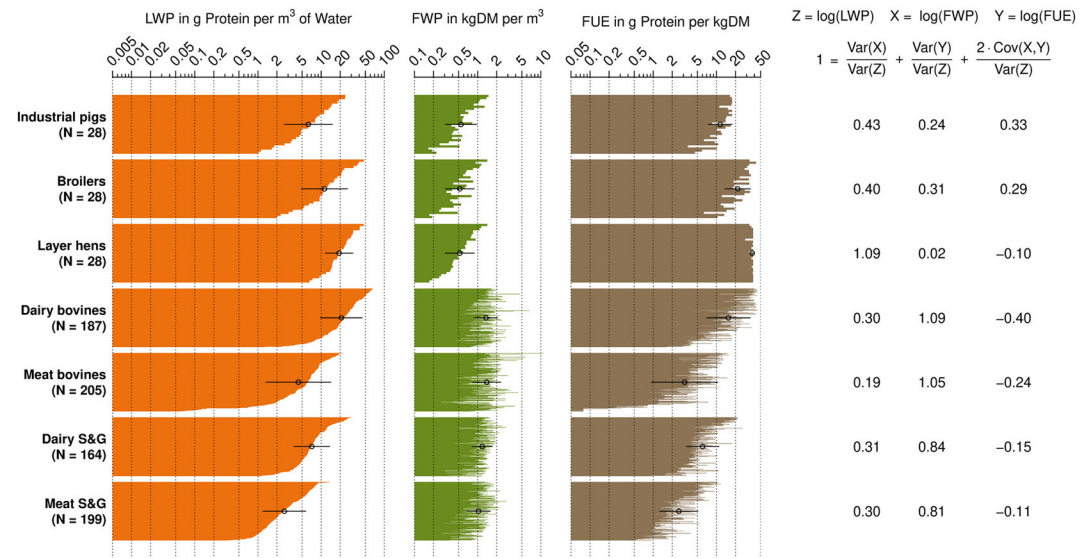
Figure 3. Livestock water productivity (LWP) and its components' feed water productivity (FWP) and feed use efficiency (FUE), all sorted by LWP. Mean and the range of ±1 standard deviation calculated from the log-transformed variables are indicated (black open dot with whiskers for standard deviation). The table shows the relative contribution of variance in FWP, variance in FUE, and double covariance of FWP with FUE to variance in LWP. Because LWP is the product of FWP and FUE, all variances are calculated from log-transformed variables (see Text S6 for details).

contribution to total CWU and production. Smallholder pigs and poultry are omitted, because FWP and FUE cannot be calculated for these due to the contribution of feed from unaccounted sources. Also, all values for the Pacific Islands region have been excluded as most estimates in this region appear extreme or even implausible, probably due to unreliable FAO statistics of feed use, animal numbers, and production.

3.3.1. Contribution of Variations in FWP and FUE to Variations in LWP

In Figure 3, the LWP in different regions and production systems is shown sorted from high to low, along with the corresponding distribution of FWP and FUE (all values in the same order as LWP) for each livestock production type. The logarithmic representation is required to overcome the difference in scale and magnitude, so that it is possible to visually and statistically analyze the variations in LWP, FWP, and FUE.

By comparing the patterns of log(FWP) (green), log(FUE) (brown), and log(LWP) (orange) in Figure 3, it is possible to draw conclusions about how differences in FWP and FUE determine the variations of LWP. For industrial pigs and broilers, the histograms of log(FUE) and log(FWP) (ordered from high to low LWP) both exhibit a similar gradient from high to low, indicating not only that they contribute about equally to variations in LWP but also that they are to some degree correlated. For layer hens, FUE is more or less constant across regions and the gradient of log(FWP) closely resembles the gradient of log (LWP), indicating that variations in LWP are almost entirely caused by differences in FWP. For ruminants, variations in log(FUE) are generally larger than variations in log(FWP) (indicated by the range of ±1 standard deviation in Figure 3). Accordingly, the histogram of log(FUE) shows a similar gradient from high to low as log(LWP), whereas the distribution of log(FWP) appears to be more or less random in relation to LWP.

Decomposition of total variance of log(LWP) into variance of log(FWP), variance of log(FUE), and double covariance between covariance of log(FWP) with log(FUE) (table in Figure 3; see Text S5 for details) confirms the visual interpretation of Figure 3 and reveals further details that support the assessment of potentials to improve LWP. The covariance component therein can be interpreted as the contribution of correlation between FWP and FUE to total variance. For industrial pigs and broilers, the contribution from variance in log(FWP) (column 1) is larger than the contribution from variance in log(FUE) (column 2), which means that the potential to increase LWP by increasing FWP is larger than that by increasing FUE. However, for improving LWP, it is also important to know how much of the variation in FWP and LWP can be addressed through management. Because animal housing allows for complete control of environmental conditions, FUE in industrial pig and broiler production can in principle be increased to the observed maximum in

any part of the world with optimal management, whereas differences in environmental conditions will always result in variations of FWP even under optimal management. Mueller et al. (2012) have estimated that for most major crops the differences in management explain 60% to 80% of yield variability and that global crop production of these crops could be increased by 47% to 70% by improving nutrient and water management. Given that the response of FWP to increasing yield is not linear (Rockström et al., 2007) and that improvements in FWP can also be achieved through agricultural water management (Jägermeyr et al., 2016), these numbers should not be directly interpreted as the potential to improve FWP, but they clearly highlight the importance of crop management for increasing LWP through improvements of FWP. For industrial layer hens, the contribution of log(FUE) to log(LWP) is very small, which means that variations in LWP are almost entirely determined by variations in FWP, so that LWP can only be improved by increasing FWP.

The dominant influence of variations in FUE for causing the variations in LWP of ruminants is the result of both a lower variance of FWP and a higher variance of FUE for ruminant types compared to industrial pigs and poultry. The lower variance in FWP for ruminants is caused by the low variance of WP of grazed biomass (44% lower than for feed crops), which on average make up about 68% of ruminant feed. This also means that the potential to increase FWP of ruminant feed is much smaller than for industrial pigs and poultry, not only because variance in FWP is lower but because WP of grazed biomass as defined here (Text S5) is entirely the result of environmental conditions and not subject to management. The high variance in FUE of ruminants is primarily the result of the diversity in ruminant management across regions and production systems, from smallholder ruminant rearing in developing countries to commercial production in high-income countries (Herrero et al., 2013). Variance of log(FUE) is especially large for meat and also dairy bovines. This implies a large potential to increase LWP for ruminants and particularly for meat and dairy bovines by increasing FUE. Although ruminants often spend at least part of their lifetime grazing on pastures where they are exposed to environmental conditions, it is in principle possible to minimize the exposure to unfavorable climatic conditions by providing suitable shelter or rear ruminants entirely indoors. Thus, FUE can in principle be increased to its theoretical maximum in any part of the world, but doing so may not always be practical.

3.3.2. Causes and Implications of Correlation Between FWP and FUE

If FWP and FUE were unrelated, the variance of log(LWP) would be the sum of only variances of log(FWP) and log(FUE). However, for all livestock production types in our analysis, we find correlations between FUE and LWP of varying signs and strengths, which amplify or diminish the variance of log(LWP) by the double covariance between log(FWP) and log(FUE) (Figure 3, column 3; see Text S6 for details). For industrial pig and broilers, about one third of total variance of log(LWP) can be attributed to a positive correlation between FWP and FUE. For all other livestock production types, a negative correlation between FWP and FUE results in a reduction of variance of log(LWP).

Understanding the underlying reasons for these correlations is crucial for assessing their implications for LWP improvements. Given the design of the study and the data and models used, three major drivers can be expected to cause a correlation between FWP and FUE in the results presented here: environmental conditions, socioeconomic context, and feed composition. All livestock species are sensitive to climatic stress, in particular heat stress under high temperature and humidity (Nardone et al., 2006), leading to decreased overall productivity. Temperature extremes also affect plant growth and development (Hatfield & Prueger, 2015), but many other abiotic factors such as soils, insolation, and precipitation are only relevant for crops and grasses and have no direct impact on livestock. Thus, variations in temperature can cause positive correlation between FUE and FWP, but the effect is possibly small. A much stronger influence on the correlation between FUE and FWP can be expected from the socioeconomic context in which feed cultivation and livestock rearing take place. Although crop-based feed is also traded internationally, the vast majority of feed is grown domestically (FAO, 2018). Thus, access to capital, knowledge, and technology within a country determine how well both feed crops and livestock are managed, causing FUE and FWP to become positively correlated. Finally, variations in the composition of feed can cause FUE and FWP to be negatively correlated, when feed components with a high nutritional value (e.g., maize and soya) lead to a higher FUE and lower FWP, because they provide more energy to livestock but require more water to be grown.

3.3.2.1. Correlation Between FWP and FUE for Industrial Pigs and Poultry

The effect of climatic conditions on the correlation between FUE and FWP found for industrial pigs and poultry is most likely negligible because these livestock types are usually reared indoors (Herrero et al., 2013). Also, FUE for monogastric animals was estimated from literature and does not account for differences in

composition or quality of feed (Herrero et al., 2013). Thus, the positive relationship between FWP and FUE for industrial pigs and broilers is most likely attributable to the influence of the socioeconomic context on crop and livestock management. This is supported by a strong correlation of FWP and FUE with regional per capita gross domestic product (GDP), which is here taken as a proxy for the socioeconomic development level (Spearman's rho all between 0.57 and 0.59, $p < 0.01$; see Table S4). There is no obvious explanation for the inverse relationship between FWP and FUE found for industrial layer hens. They receive the same feed mix as industrial broilers, so their FWP shows the same strong correlation with GDP, but correlation of FUE with GDP is negative (Spearman's rho -0.35, $p > 0.05$).

Because the positive relationship between FWP and FUE of industrial pigs and broilers in Figure 3 is the result of a common socioeconomic context, an improvement of FWP and FUE by appropriate management interventions will not lead to a parallel improvement in FUE and FWP, respectively, and the management gaps causing variations in FWP, FUE, and eventually LWP have to be addressed individually. However, both FWP and FUE would benefit from improved socioeconomic conditions that facilitate intensification in the agricultural sector. Even if a causal relationship for the negative correlation between FWP and FUE cannot be ruled out, the contribution of covariance between log(FWP) and log(FUE) to total variance of log(LWP) is very small, making it unlikely that improvements in FWP through targeted management interventions or a trend toward intensification would be substantially offset by a corresponding decreases in FUE.

3.3.2.2. Correlation Between FWP and FUE for Ruminants

The influence of socioeconomic context on the correlation between FUE and FWP can be expected to also apply for ruminants, but because most of ruminant feed is grazed biomass, whose WP is not influenced by management in our analysis, the overall effect is probably weaker. Environmental conditions, on the other hand, are likely to also play a role as most ruminants spend at least part of their lifetime grazing on pasture, where they can become exposed to climatic stress. However, both are drivers that lead to positive correlation between FUE and FWP, while the correlation found in Figure 3 for ruminants is negative. Because ruminants are fed a wide variety of feed mixes—composed of components with very different nutritional quality and water requirements—and because the influence of feed quality on FUE is explicitly accounted for in the data from Herrero et al. (2013), inverse effects of feed composition on FWP and FUE are a likely explanation for a negative correlation between FWP and FUE.

In Figure 4, the effect of supplementation with feed crops on FWP, FUE, and resulting LWP is shown for all ruminant types. Adding crop-based feed with a high energy and protein content to the primarily grass-based diet of ruminants improves the nutritional value of the whole feed mix and leads to an increase in FUE (brown, middle row). But because the WP of crops is much lower than the WP of grass (0.62 kgDM/m^3 in average for crops compared to 1.45 kgDM/m^3 for grazed biomass), this comes at the cost of a lower overall FWP (green, top row). Since the increase in FUE is stronger than the decrease in FWP, supplementation with feed crops always results in a higher LWP compared to an entirely roughage-based diet (orange, bottom row). However, at least for bovines, FUE gains from supplementation with feed crops appearing to diminish at high crop shares, so that LWP reaches a maximum at about 20% feed crops in the feed mix and declines thereafter.

Akin to supplementation with feed crops, the incorporation of crop residues (straws and stovers) in ruminant feed also influences FWP and FUE, but with opposite sign (Figure 5). Due to low nutritional value and the assumed no water cost, feeding crop residue to ruminants has a positive effect on FWP and a negative effect on FUE. Although the strength of both effects is similar over the considered range of residue shares, it appears that moderate inclusion of crop residues (up to about 30%) into feed of bovines tends to have a negative effect on LWP, whereas higher shares lead to an increase in LWP. The latter is caused by a strong increase in FWP for high shares of crop residues, which is the consequence of the assumption of no water cost for residues (for a diet consisting entirely of crop residues, FWP would approach infinity). For sheep and goats, the smaller range of residue shares in the data set and the limited number of data points hamper the identification of a pattern in LWP to feeding crop residues, but it is likely that it follows a similar general pattern than for bovines.

Although the responses of FUE and FWP to crop and crop residue supplementation in Figures 4 and 5 can be fully explained by the consequences of varying feed composition, they are also influenced by other aspects of crop and livestock management. We find that the share of feed crops is positively and the share of crop
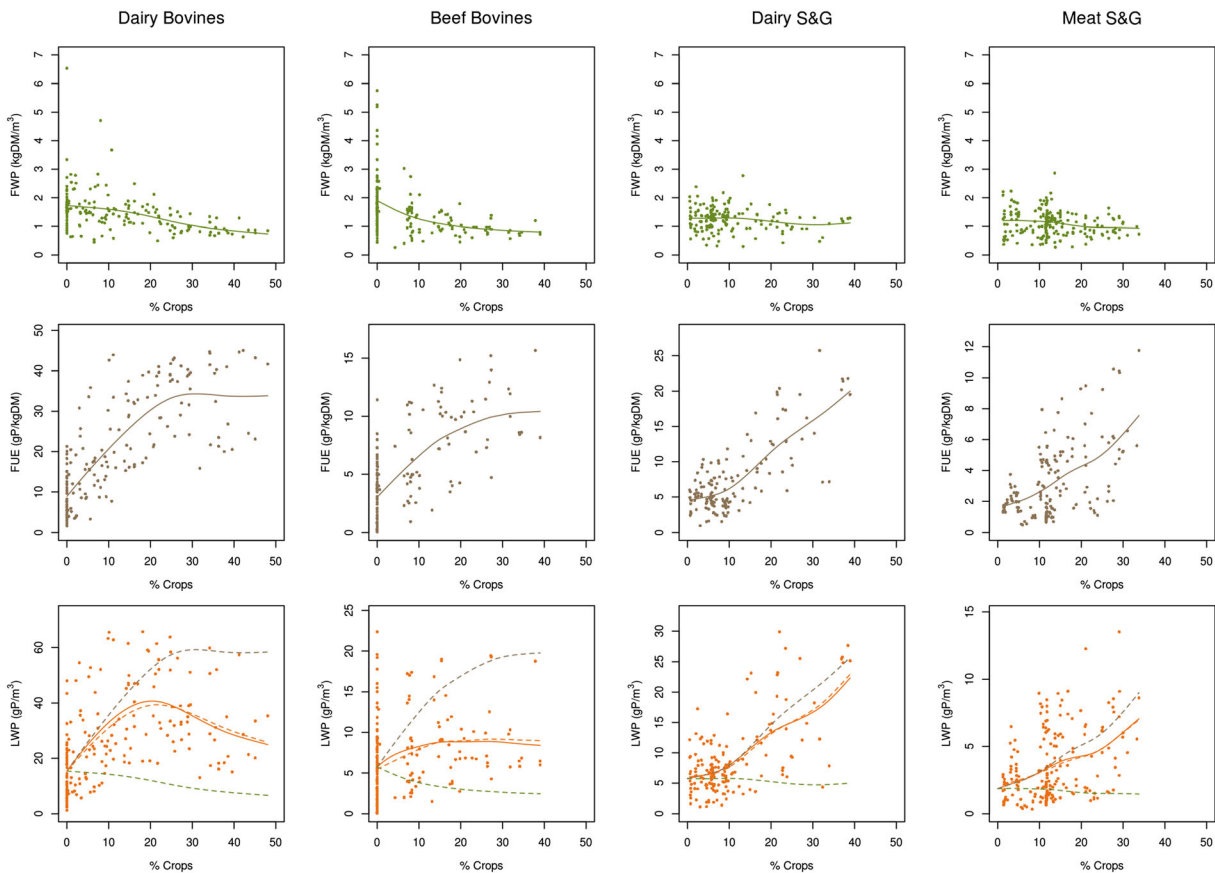
Figure 4. Relationship between the percentage of crop-based feed (grain, concentrates) in the feed mix of ruminants and FUE and FWP, and the resulting effect on LWP. Solid lines are smoothing splines directly fitted to the data. Dashed lines in LWP (bottom row) are the product of the splines fitted to FWP and FUE (orange), the product of the spline fitted to FWP and constant FUE for 0% grain use (brown), and the product of the spline fitted to FUE and constant FWP for 0% grain use (green).

residues in the feed mix is negatively correlated with GDP for all ruminant types (Spearman's rho 0.38 to 0.64 for the fraction of feed crops and −0.28 to −0.43 for the fraction of crop residues; see Table S4), so that high rates of supplementation with feed crops tend to be associated with a high overall level of intensification in both crop and livestock production, whereas high rates of residue use tend to be associated with a low level of agricultural intensification. These correlations contribute to the observed relationships of FWP and FUE with crop supplementation by diminishing the decline of FWP and enhancing the increase of FUE. Likewise, the observed decline of FUE in response to incorporation of crop residues in feed is to some degree attributable to poorer overall livestock management. Therefore, specific features of the pattern in Figures 3 and 4 such as the apparent maximum of LWP at 20% crop supplementation and the apparent minimum of LWP at 30% residue incorporation for bovines are merely emergent characteristics of the global livestock sector in 2000 and must not be mistaken as an indication for an optimal feed composition.

Regardless of the unquantified contribution of crop and livestock management to the relationships in Figures 3 and 4, direct effects of feed composition on FUE and FWP are fundamental mechanisms that lead to a trade-off between improving FUE or FWP through feed composition at the cost of lower FWP or FUE, respectively. Optimizing the feed mix of ruminants in a specific setting bears a great potential for improving LWP but requires detailed knowledge about the response of FUE to changes in feed composition and about water requirements for producing the different feed components. For reaping maximum benefits, the inter-actions between feed mix and other crop and livestock management aspects need to be considered, as these can drastically change the responses of FWP and FUE (e.g., better crop management can compensate a drop in FWP and better livestock management can enhance the FUE increases thorough feeding interventions). And technological innovations, such as pre-treatment of residues to improve their nutritional quality
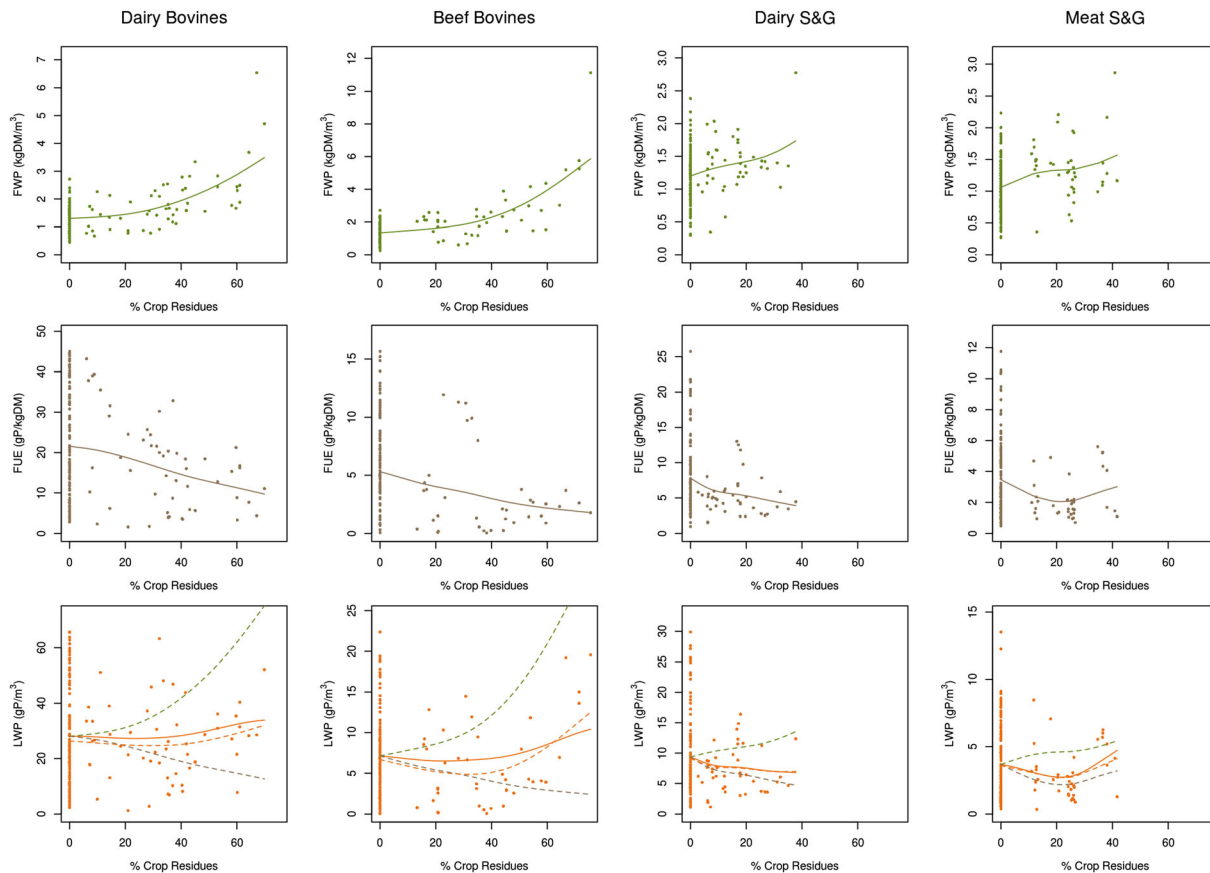
Figure 5. Relationship between the percentage of crop residues used in the feed mix and FUE and FWP, and the resulting effect on LWP. Solid lines are smoothing splines fitted to the data. Dashed lines in LWP (bottom row) are the product of the splines fitted to FWP and FUE (orange), the product of the spline fitted to FWP and constant FUE for 0% stover use (brown), and the product of the spline fitted to FUE and constant FWP for 0% stover use (green).

(Blümmel et al., 2018), can potentially weaken or resolve the trade-off between FWP and FUE. In specific applications, it is also critical to reassess the validity of the water allocation rules applied in our global study. For example, assigning no water to residues could lead to misleading conclusions when using crop residues for feed causes nutrient mining from agricultural soils (Lutz et al., 2019).

Our results suggest that LWP of ruminants, unlike for industrial pigs and poultry, does not always benefit from a trend toward intensification in the whole agricultural sector. Because better overall livestock management tends to be associated with high rates of supplementation with feed crops, the corresponding decline in FWP can lead to a lower LWP in intensively managed systems.

3.4. Comparison With ET and CWU Estimates From Literature

Our estimate of total cropland ET (8,552 km^3/yr) is lower than the estimates reported by Hanasaki et al. (2010) and Siebert and Döll (2010) but larger than the estimate by Liu and Yang (2010) (Table 1). Since all these estimates are based on the same cropland data set (Ramankutty et al., 2008), the difference should be attributable to other input data and model formulations used here. However, the estimate of fallow ET from Liu and Yang (2010) appears very low and probably only includes ET from cropland outside the growing period, whereas our and the other estimate also include ET from land not cultivated every year. The share of fallow ET in total cropland ET in our analysis is 36%, which agrees well with the corresponding estimates of 36% and 32% from Hanasaki et al. (2010) and Siebert and Döll (2010), respectively.

Our estimate of 5,447 km^3/yr for ET during the growing period is somewhat below the range of estimates reported by all other studies (5,938–7,130 km^3/yr). This is consistent with the general underestimation of ET by LPJmL4 (Schaphoff, Forkel, et al., 2018), although at least two of the studies (De Fraiture, 2007; Weindl et al., 2017) also make different assumptions about cropland extent and area harvested. The share

Table 1
Estimates of ET Components From Cropland and Pastures and CWU Components Allocated to Livestock

Component	De Fraiture et al. (2007)	Mekonnen and Hoekstra (2011, 2012)	Hanasaki et al. (2010)	Liu and Yang (2010)	Siebert and Döll (2010)	Weindl et al. (2017)	Our study
Year	2000	1996–2005	2000	1998–2002	1998–2002	2000	1998–2002
ET cropland			11,070	7,323	9,823		8,552
ET fallow			3,990	1,385	3,137		3,105
ET growing period	6,690	6,670	7,080	5,938	6,685	6,100	5,447
Crop ET from blue sources (%)	16.9	13.5	21.6	15.6	17.7	16.6	16.2
Total CWU barley		200			161		137
Total CWU maize		648			693		684
Total CWU wheat		964			858		652
Total CWU soybeans	427	363			399		230
Total CWU crops for livestock	1,312	1,304				2,170	1,686
ET Pastures			12,960			16,520	11,252
Green CWU grazing	840	913				2,590	1,688

Note. To facilitate comparison of estimates from different studies, the values reported in this table do not account for the consumptive losses of irrigation. Likewise, the estimates of total CWU for individual crops and crops for livestock feed do not include fallow ET. All ET and CWU totals are in km^3/yr.

of 16% crop ET from blue water sources in our analysis is close to the estimates from four other studies and equivalent to the average across all studies (17%). Our estimate of 387 km^3/yr consumptive blue water losses from irrigation water supply infrastructure, which is not included in the figures shown in Table 1, is close to the corresponding estimate of 440 km^3/yr from De Fraiture et al. (2007).

When looking at total growing period CWU for barley, maize, wheat, and soybeans, we find that the sum of ET estimated for these four important feed crops in our analysis is about 20% lower than the sum of the corresponding estimates from Mekonnen and Hoekstra (2011) and Siebert and Döll (2010). For barley, wheat, and soybeans, the difference between our estimates and the two other studies is quite large, but there are also large differences between Mekonnen and Hoekstra (2011) and Siebert and Döll (2010). Our estimate for total growing period CWU for maize is nearly identical to the estimate from Siebert and Döll (2010) and slightly larger than the estimate from Mekonnen and Hoekstra (2011). The differences between estimates from different studies can in part be attributed to different assumptions about the harvested area of crops as well as differences in terms of start and length of growing periods. However, one fundamental difference between the two other studies and ours is that LPJmL4 can account for changes in ET due to differences in crop leaf area index under different crop management intensities, whereas Siebert and Döll (2010) and Mekonnen and Hoekstra (2011) estimate ET based on fixed crop factors that do not vary with management.

The share of crop ET allocated to CWU of livestock production in our analysis is 31%, which is much larger than the corresponding estimates of 18% and 20% from De Fraiture et al. (2007) and Mekonnen and Hoekstra (2012), respectively, and slightly lower than the 36% estimated by Weindl et al. (2017). Neither De Fraiture et al. (2007) nor Mekonnen and Hoekstra (2012) provide sufficient information that could help to explain their low shares of crop ET allocated to livestock production. However, according to FAOSTAT, 70% of barley, 67% of maize, and 18% of global wheat production are used for feed and account together for 44% of total concentrate feed used for livestock production. Applying these shares to CWU estimates for these crops from Mekonnen and Hoekstra (2011) would allocate about 750 km^3/yr of ET to livestock production alone. Together with their 600 km^3/yr of ET for "fodder crops" (Mekonnen & Hoekstra, 2011), this amounts to more than the total crop ET allocated to livestock production by Mekonnen and Hoekstra (2012). Only a small part of this discrepancy can be explained by their higher than average feed used in countries with a lower than average CWU per kg feed, which results in less ET attributed to feed when country-specific values are used (about 20% in our analysis). More important is the assumed use of concentrate feed in livestock production (1 Gt/yr in total) in Mekonnen and Hoekstra (2012), which is very low compared to the about 1.3 Gt/yr of concentrate feed used in livestock production according to FAOSTAT and in our analysis. Thus, our higher share of crop ET attributed to livestock production appears more realistic in light of FAO statistics.

Estimates of ET from pastures varies greatly among studies, which can be primarily attributed to differences in the assumed distribution and extent of pasture lands, which is highly uncertain (Fetzel et al., 2017).

However, the assumed pasture extent has little importance for the estimation of livestock CWU as only the ET related to biomass actually grazed by ruminants is accounted for. Estimates of CWU for grazed biomass are basically determined by the estimated grazing requirement and the WP of pastures. The grazing demand from Herrero et al. (2013) used in our analysis is 2.4 Gt/yr, and the average grass WP is 1.45 kg/m^3. The estimate from De Fraiture et al. (2007) assumes a global constant grass WP of 1.3 kg/m^3 so that grazing demand must be about 1.1 Gt/yr—less than half than in our study. According to Schyns et al. (2019), Mekonnen and Hoekstra (2012) assumed a grazing demand of 2.8 Gt/yr, which implies a global average grass WP of more than 3.0 kg/m^3—a value achieved on less than 3.5% of global pastures in our analysis. Weindl et al. (2017) estimate a grazing CWU of 2,930 km^3/yr in 2010 for a grazing demand of 4.0 Gt/yr, which corresponds to an average grass WP of 1.35 kg/m^3. While average grass WP agrees well with our estimate, grazing demand is much higher than in any other study. While most of their CWU estimates for crops are taken from Mekonnen and Hoekstra (2012), Schyns et al. (2019) provide a revised estimate of grazing CWU of 2,620 km^3/yr for the year 2000 that attempts to account for the declining (monetary) value of some ecosystem services with increasing grazing intensity. This much larger estimate than ours is partly explained by their slightly larger grazing demand of about 2.7 Gt/yr in combination with lower WP estimates from Rolinski et al. (2018), but it is also the result of their novel approach. However, the value assigned to grassland ecosystem services and how they change with grazing intensity are based on global estimates and an assumed linear response.

4. Conclusions

We combine estimates of animal feed consumption and production from Herrero et al. (2013), estimates of CWU for the various feed types simulated with LPJmL4 (Schaphoff, von Bloh, et al., 2018b), and FAO statistics (FAO, 2018), to compute livestock CWU and LWP for 918 different production units representing the global livestock sector. An important novelty is that our estimates of CWU for crops and livestock include the ET that occurs outside the growing season of crops from fallow land. This allows for a straightforward comparison between CWU estimates for seasonal and perennial crops and across production systems with different cropping intensity.

Our results show that, annually, 4,387 km^3 of water is required to produce the feed consumed by the global livestock sector, equaling about 22% of the total ET from global agricultural lands and 42% of total agricultural CWU appropriated for human use. About 77% of this water is ET during the growing season of crops and grass, and the remainder is ET from fallow land and transportation losses of irrigation water. With blue water contributing only about 6% to total livestock CWU, the livestock sector is primarily green water dependent. About half of the green water is ET from pastures, of which one third occurs from pastures on marginal land with no alternative use in crop production.

Our analysis reveals huge differences in LWP both among and within different livestock types. By analyzing the interaction of variations in FWP and FUE to produce the variations in LWP, we find that variations in LWP of industrial pigs and broilers are to a similar extent caused by variations in both FWP and FUE, that variations in LWP of industrial layer hens are almost exclusively determined by variations in FWP, and that variations in LWP of ruminants are dominated by variations in FUE though with substantial contributions from variations in FWP. About one third of variability in LWP of industrial pigs and broilers is caused by a correlation between FWP and FUE, and variations in LWP of bovines and, to a lesser degree, sheep and goats are dampened by a negative correlation between FWP and FUE.

The variability in FUE of industrial pigs and broilers in our analysis can be entirely attributed to different management and corresponding efficiency gaps that could be addressed by appropriate livestock management interventions. Variability in FWP is the result of differences in both management and environmental conditions, which means that variations in FWP can only partially be reduced by improved crop and land management. Although FUE and FWP are correlated, they are not causally linked, meaning that improvements in either factor will not lead to an improvement in the other factor. Variability of LWP for industrial layer hens is much smaller than that for other monogastric livestock types and are almost entirely the result of variations in FWP. Since only the part of the variations in FWP that are not related to different environmental conditions can be reduced through management, the overall potential to increase LWP for layer hens is comparatively small.

Variability of LWP for ruminants is dominated by variations in FUE, which are mainly caused by differences in livestock management and may thus be greatly reduced by closing efficiency gaps through appropriate management improvements in the livestock sector. Variability in FWP is much smaller than for pigs and poultry and more strongly determined by environmental conditions, which implies a comparatively small potential to improve LWP of ruminants through interventions aiming at improving FWP. However, because we did not account for the effect of pasture management on WP of grazed biomass, the potential to improve FWP of ruminants through improved pasture management was not assessed. The negative correlation between FUE and FWP found for all ruminant types can be mainly attributed to opposite effects of feed composition on FUE and FWP: Improvements in FUE through supplementation with feed crops are accompanied by a reduction in FWP due to the lower WP of feed crops compared to grass. And improvements in FWP through incorporation of crop residues are offset by lower FUE caused by their lower nutritional value. However, to determine the feed composition that results in the best LWP in a specific production system requires detailed knowledge of the nutritional value of the different feed components, the water requirements to produce them, and how animals respond to changes in the feed mix. To avoid pitfalls that may arise from the generic rules for allocating water to crop residues and grazed biomass used in our study, efforts to improve LWP in a specific situation must also involve a careful consideration of these rules—including an evaluation of the benefits derived from unused residues and grass biomass. Last but not least, seasonal variations in feed demand and composition (e.g., during lactation) as well as seasonal variations in feed availability (in particular, grazing) need to be considered and addressed through management, if possible.

The availability of data limits our analysis to around the year 2000. This affects the validity of our estimates of CWU and LWP as a depiction of the present-day conditions in the livestock sector. However, we consider the analysis of variations in LWP, their attribution to FUE and FWP, and the identified opportunities and limitations for improving LWP as being fully applicable to today's livestock sector.

Data Availability Statement

The core output of the analysis in this paper—consisting of estimates of consumptive water use from three different sources in 919 global units—has been made available under a Creative Commons Attribution 4.0 License and is available for download from http://doi.org/10.5281/zenodo.4265089 (Heinke et al., 2020). Following the guidelines of the German Research Foundation for safeguarding good scientific practice (German Research Foundation, 2019), all data and code required to reproduce the results in this publication will be archived at the Potsdam Institute for Climate Impact Research for at least 10 years. The Potsdam Institute for Climate Impact Research will make this data available to anyone upon request.

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