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BOARD-INVITED REVIEW: Quantifying water use in ruminant production[1]

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ABSTRACT: The depletion of water resources, in terms of both quantity and quality, has become a major concern both locally and globally. Ruminants, in particular, are under increased public scrutiny due to their relatively high water use per unit of meat or milk produced. Estimating the water footprint of livestock production is a relatively new field of research for which methods are still evolving. This review describes the approaches used to quantify water use in ruminant production systems as well as the methodological and conceptual issues associated with each approach. Water use estimates for the main products from ruminant production systems are also presented, along with possible management strategies to reduce water use. In the past, quantifying water withdrawal in ruminant production focused on the water demand for drinking or operational purposes. Recently, the recognition of water as a scarce resource has led to the development of several methodologies including water footprint assessment, life cycle assessment, and livestock water productivity to assess water use and its environmental impacts. These methods differ with respect to their target outcome (efficiency or environmental impacts), geographic focus (local or global), description of water sources (green, blue, and gray), handling of water quality concerns, the interpretation of environmental impacts, and the metric by which results are communicated (volumetric units or impact equivalents). Ruminant production is a complex activity where animals are often reared at different sites using a range of resources over their lifetime. Additional water use occurs during slaughter, product processing, and packaging. Estimating water use at the various stages of meat and milk production and communicating those estimates will help producers and other stakeholders identify hotspots and implement strategies to improve water use efficiency. Improvements in ruminant productivity (i.e., BW and milk production) and reproductive efficiency can also reduce the water footprint per unit product. However, given that feed production makes up the majority of water use by ruminants, research and development efforts should focus on this area. More research and clarity are needed to examine the validity of assumptions and possible trade-offs between ruminants' water use and other sustainability indicators.

Key words: life cycle assessment, livestock, ruminant, water footprint, water productivity

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GENERAL INTRODUCTION

The current global human population is predicted to grow by 30%, from 7.3 billion in 2015 to 9.7 billion by 2050, with much of the growth occurring in less developed nations (United Nations, Department of Economic and Social Affairs, Population Division,

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2015). Global household incomes are also expected to grow, especially as less developed regions become more prosperous. As a consequence, the demand for food and feed crops is predicted to nearly double in the coming 50 yr (International Water Management Institute, 2007). This will be accompanied by an increasing demand for water for food and feed production.

Although about three-fourths of the earth's surface is covered by water, and about 2.5% of this is freshwater, most of which is unavailable because it is captured in ice caps, glaciers, or deep underground (Shiklomanov, 1993). The freshwater available in the form of surface water (i.e., about 1.2% of all freshwater) or shallow groundwater is not evenly distributed among nations or across regions within a nation, making water management both a global and a local issue. Water is considered to be a renewable resource because it cycles through land, water bodies, and the atmosphere. However, in many areas, water is drawn from water bodies for various purposes such as domestic use and irrigation faster than it can be recharged through precipitation. The depletion of water resources, not only in terms of quantity but also in terms of quality, has become an issue of global concern. In addition, many nations with severe water shortages are experiencing high population growth. An estimated two-thirds of the current global population live under conditions of severe water scarcity at least 1 mo of the year, and half a billion people face severe water scarcity all year round (Mekonnen and Hoekstra, 2016). In the coming decades, the proportion of people living in water-stressed regions is expected to rise significantly (Wada et al., 2014). Furthermore, climate change is projected to negatively impact the availability and quality of water in many parts of the world (Jiménez Cisneros et al., 2014). Consequently, identifying techniques to effectively manage water resources and address scarcity issues resulting from excessive withdrawals and contamination has become a key global issue (Mazzi et al., 2014).

RUMINANT LIVESTOCK AND WATER USE

Given the above observations, the demand for livestock products is expected to rapidly increase so as to meet the demand for protein and satisfy dietary preferences (FAO, 2011). Ruminants play a crucial role in food production worldwide by making use of plant resources, such as grasses, from which humans can derive little nutritional value. They also make use of nutrients in food byproducts, thereby reducing the waste disposal problem. In addition, forage-based systems are known for their multiple ecological benefits, such as enhancing biodiversity, water quality, soil health, and carbon sequestration (Guyader et al., 2016). Ruminant production has also been reported to intensively use water for drinking, growing feed crops or forages, waste disposal, general cleaning, and processing of products.

Quantifying the water footprint of anthropogenic activities involving ruminant production is a relatively new field of research where methodologies are still developing. The term "water footprint" was coined in the early 2000s as an indicator of the volume of freshwater used to produce food (e.g., meat, milk) or an industrial product (Hoekstra and Hung, 2002). Interest in water use of animal products has grown in the last 2 decades partly in response to consumer concerns about the environmental impacts of food production (Pimentel et al., 1997; Chapagain and Hoekstra, 2003; Hoekstra, 2012; Ridoutt et al., 2012). Although assessments using the concepts of "virtual water" and "water footprint" suggest that animal products generally have a higher water footprint than plant-based products (Allan, 1998; Ercin et al., 2012; Mekonnen and Hoekstra, 2012), there are large discrepancies in the values reported as well as differences in assessment methods. The main objectives of this literature review are to 1) describe and critically analyze approaches to quantify water use in ruminant production including water footprint assessment (**WFA**) and life cycle assessment (**LCA**), 2) summarize and compare water use estimates of ruminant products from a range of studies, and 3) identify and analyze possible strategies to reduce the water use of livestock products.

LIVESTOCK–WATER INTERACTIONS

Approximately 60 to 70% of an animal's body mass is water (Naqvi et al., 2015). Water is vital for essential physiological and biochemical processes of ruminants such as thermoregulation, transport, purification, growth, reproduction, and lactation, with the requirement increasing as the productivity of the animal increases (Alemayehu et al., 2012). Water requirements are met primarily through drinking water and the inherent presence of water in consumed feedstuffs, with a relatively smaller contribution of metabolic water produced by the oxidation of nutrients. Although an animal may lose a significant portion of its body fat and over 50% of its protein without serious health consequences, a loss of 10 to 20% of water body mass causes severe health disorders and even death (Scott et al., 1976; Maynard et al., 1979; Cunha, 1991). In addition to water needed to satisfy an animal's requirements, a significantly greater quantity is used for feed production, with further requirements relating to manure management, product processing, and sanitation (Chapagain and Hoekstra, 2003; Blümmel et al., 2014). Feed production can affect water flows through the abstraction of surface or groundwater for irrigation, land cover changes (e.g., when forests are converted to cultivated croplands

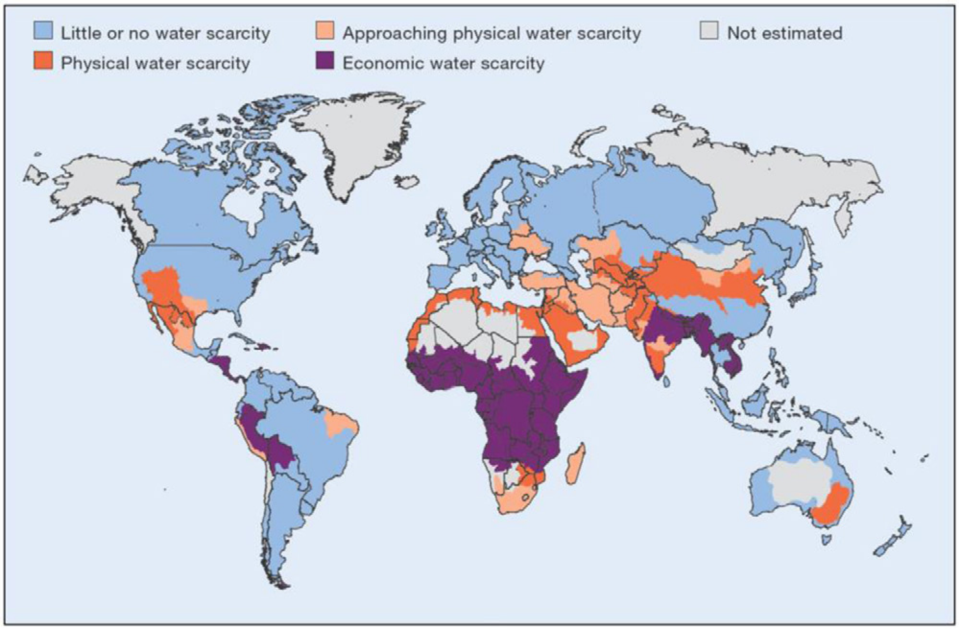

Figure 1. Global map of water scarcity at the basin level in 2007 (source: International Water Management Institute , 2007). River basins are the geographic area contained within the watershed limits of a system of streams and rivers converging toward the same terminus. Definitions and indicators: little or no water scarcity: abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes; physical water scarcity (water resources development is approaching or has exceeded sustainable limits): more than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows); approaching physical water scarcity: more than 60% of river flows are withdrawn and these basins will experience physical water scarcity in the near future; economic water scarcity (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands): water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

or pasturelands), and changes in land use management influencing soil characteristics (Deutsch et al., 2010).

Ruminants release nitrogen, phosphorus, microbes, and other substances that can reach surface water or groundwater (FAO, 2009). However, their effect on water quality depends on management, including if application of manure and fertilizer is aligned with crop nutrient needs and if stocking rate is aligned with the carrying capacity of pastureland. Well-managed pasturelands can protect the soil surface from erosion to a greater extent than cultivated crops, whereas poor range management practices may degrade water quality through erosion, sedimentation, and transport of nutrients and pathogens into surface waters (Hubbard et al., 2004). Often, the impact of agriculture on water quality is relative, because it should be considered in relation to alternative activities. For example, access of ruminants to sensitive wetlands damages biodiversity to a lesser extent than draining wetlands and converting them to annual crop production (Doreau et al., 2012).

Increasing demand for livestock products and rising livestock numbers are projected to exert growing pressure on freshwater resources. In some arid areas where crop production is not viable due to the scarcity and uneven distribution of water, grazing livestock may be the only feasible means of making use of erratic rainfall for food production that would have otherwise been unused (Cook et al., 2009). Regions of the world that experience severe physical or economic water scarcity, particularly those in sub-Saharan Africa and southern Asia (Fig. 1), also have greater density of large ruminants (Fig. 2). Quantifying the water use associated with ruminant production and their products is a crucial step for identifying strategies for sustainable use of available water resources and avoidance of expanding desertification.

METRICS AND TOOLS FOR QUANTIFYING WATER USE IN RUMINANT PRODUCTION

Water Demand Assessment: The Conventional Approach

Estimating the amount of water required or consumed by agricultural activities including ruminant production is not a new undertaking. However, most of the earlier efforts were based on direct water use by ruminants with little regard for environmental sustainability. For example, the U.S. Geological Survey has reported the approximate amount of water used for irrigation and livestock every 5 yr since 1950 to estimate the total quantity of water withdrawn at a state and/or national level (MacKichan, 1951; Maupin et al., 2014). Activities considered in the most recent calculations include livestock watering, cooling of facilities for animals and their products, dairy sanitation and wash down of facilities, manure disposal systems, and in-

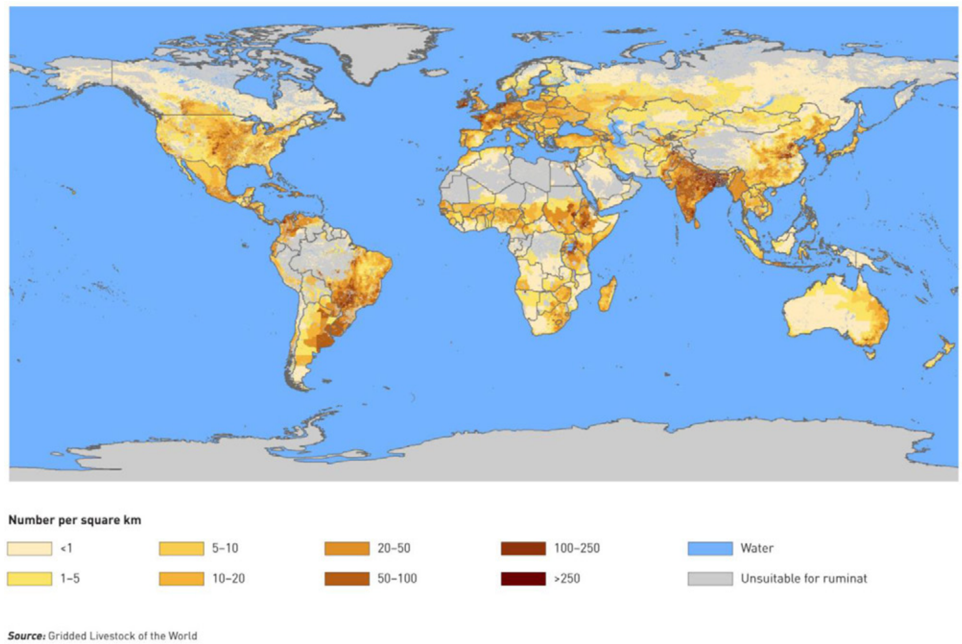

Figure 2. Global cattle density map (FAO, 2016).

cidental water losses (Maupin et al., 2014). These reports do not separate irrigation water used to produce feed from that use to produce food. In addition, estimates of water use in the reports are aggregated values derived primarily using animal population data and water use coefficients for a given livestock species or type (e.g., dairy, beef).

Water requirement recommendations have been outlined in various guidelines that primarily focus on describing the nutritional needs of ruminants such as those issued for specific classes or species by the NRC. For example, water allowance recommendations for beef cattle were first outlined by the NRC in 1976 (NRC, 1976) and presented as a separate chapter by the NRC in 1984 (NRC, 1984) and in the most recent edition of the series (National Academies of Sciences, Engineering, and Medicine, 2016).

Productivity-Oriented Water Use Assessment

Productivity or efficiency is a measure of outputs (e.g., meat, milk) from a production process (e.g., ruminant production) relative to production inputs (e.g., water). Before the development of the "virtual water" concept (i.e., water embedded in a product), there were only limited, superficial attempts to approximate the water use associated with the production of a given quantity of an animal product (Thomas, 1987). One of the earliest attempts to comprehensively analyze water use per unit of ruminant product was the study conducted by Beckett and Oltjen (1993), who developed a spreadsheet-based model to estimate water use associated with cattle production in the United States. Their model included water directly consumed by different categories of cattle and water used to irrigate feed crops and pastures as well as to process beef carcasses.

Virtual Water

The term "virtual water" was developed in the mid 1990s to illustrate that importing agricultural commodities can alleviate water shortages in water-scarce regions such as the Middle East and North Africa (Allan, 1996, 1998). Therefore, virtual water refers to the water virtually embedded in an imported product (Allan, 2003). For an animal product, such as meat or milk, the term denotes the water use in the entire production chain rather than the physical water content of the final product (Chapagain and Hoekstra, 2003). When feed or an animal product is imported into a region with a deficit of freshwater, the economy of that region will spare the water that would have been needed if the feed or animal product had been domestically produced (Chapagain et al., 2006).

Water Footprint Assessment

Hoekstra and Hung (2002) proposed the "water footprint" concept and defined it as the sum of the domestic water use and net virtual water import. This approach initially estimated a given country's actual appropriation of international water resources, as opposed to conventional national water use statistics that consider water use only within a country. Hoekstra (2003, p. 14) refined the definition of water footprint as "the cumulative virtual water content of all goods and services consumed by one individual or by the individuals of one country." Furthermore, the water footprint of a product such as meat was explicitly defined as the volume of freshwater consumed or polluted at different stages of the production chain of the respective product (Hoekstra et al., 2011; Hoekstra, 2015).

The WFA approach later subdivided the water footprint of a product into 3 components: blue, green, and gray (Hoekstra et al., 2011). The blue water footprint is the net amount of freshwater consumed from surface and ground water sources (e.g., evaporation of irrigation water withdrawn from a river). The green water footprint is the amount of rainwater stored in the soil consumed (evaporated) to grow crops. Finally, the gray water footprint is the amount of freshwater required to dilute pollutants so that the quality of the water remains above agreed water quality standards (Hoekstra and Chapagain, 2008). The manual entitled *The Global Water Footprint Standard* (Hoekstra et al., 2011) describes how these blue, green, and gray waters footprints can be estimated for individual processes and products and also provides the details necessary to conduct an optional sustainability assessment. Studies conducted by Chapagain and Hoekstra (2003) and Mekonnen and Hoekstra (2012) were the first to use the WFA approach to estimate the water use associated with livestock production and livestock products at a global scale.

Livestock Water Productivity

Livestock water productivity (**LWP**) is expressed as the ratio of the net beneficial livestock-related outputs and services to the water lost through evapotranspiration (**ET**) in producing them (Peden et al., 2007). This term is sometimes used interchangeably with water use efficiency (Kebebe et al., 2015). Over the past decade, this approach has been used to assess the water efficiency of production systems in regions such as sub-Saharan Africa, where ruminants are kept for multiple purposes, and services such as milk, meat, fiber, draft, and income generation (Gebreselassie et al., 2009; Peden et al., 2009; Descheemaeker et al., 2010; Kebebe et al., 2015). Productivity estimates can be expressed from a physical perspective as the ratio of livestock output to the amount of water consumed or on economic terms as the monetary value derived per unit of water used (Sharma et al., 2015). Water productivity includes the net amount of water consumed in feed production for ruminant production, including the water lost to the atmosphere through evaporation and transpiration. Both precipitation and applied irrigation water that is not consumed is assumed to be available for other downstream uses (Sharma et al., 2015). In the context of rain-fed production systems, LWP is a measure of the ability of the production system to convert available rainwater into beneficial outputs and services (Kebebe et al., 2015).

Impact-Oriented Water Use Assessment

Life Cycle Assessment. Life cycle assessment is one of the most widely used tools to analyze the environmental impacts of a product or production system. Typically, LCA starts by defining the goal and scope of the appraisal followed by life cycle inventory (i.e., the quantification of inputs and outputs), impact assessment, and interpretation of the results (ISO, 2006).

Life cycle assessment has been used to quantify the environmental impact of water use associated with ruminant products through the entire production process (Ridoutt et al., 2012; De Boer et al., 2013). With LCA, possible environmental impacts can be assessed by either midpoint or endpoint indicators along the cause-and-effect chain. Midpoint indicators refer to potential environmental impacts in the middle of the cause-and-effect chain (e.g., water scarcity), and endpoint indicators denote damage occurring at the end of a cause-and-effect chain, such as negative impact on human health or ecosystems as a result of water use (Pfister et al., 2017). Two companion studies conducted in Australia (Ridoutt et al., 2011, 2012) were among the first to analyze the water use of ruminant production systems in the standardized framework of LCA. More recently, there have been more ruminant-related studies, most of them conducted in regions of Oceania and Asia (Zonderland-Thomassen and Ledgard, 2012; Huang et al., 2014; Zonderland-Thomassen et al., 2014). In these LCA studies, water scarcity indices were commonly used to adjust volumetric water consumption estimates for potential local environmental impacts (Pfister et al., 2009; Boulay et al., 2015). The major impact assessment categories related to water consumption in LCA include water scarcity, impacts on human health, impacts on ecosystem quality, and resource depletion (Pfister, 2015).

Ridoutt et al. (2012) evaluated 6 beef cattle production systems in southern Australia, taking into account water use for irrigating pastures and feed crops, cattle watering, production of inputs (fuels, fertilizers, etc.), and transportation processes. They further assessed potential risks to human health and ecosystem health and depletion of resources associated with beef cattle production (Ridoutt et al., 2011) using the LCA methodology of Pfister et al. (2009). Their aggregated estimates (as an index of water-use impact; i.e., water equivalent [**H_2O-eq**]) ranged from 3.3 to 221 L H_2O-eq/kg live weight (**LW**). Zonderland-Thomassen et al. (2014) studied potential environmental impacts associated with water use in beef cattle and sheep farming in New Zealand using LCA methodology with a focus on water scarcity and eutrophication. They highlighted the need to consider location-specific information to properly account for the absolute and relative implications of water scarcity and eutrophication.

The LCA approaches introduced to estimate the water use in the past decade differ in their description of environmental impacts and types of water considered. However, in recent years, the establishment of ISO 14046:2014 (ISO, 2014) has served to align the various approaches used in LCA methodology. The unifying feature associated with all LCA-based studies is that they consider the amount of blue water used for drinking, animal husbandry, and feed production as well as related environmental impacts in a spatially explicit manner.

Water Footprint Assessment as Environmental Performance Indicator. The latest guideline for WFA provides details on how to undertake an optional sustainability assessment of water use (Hoekstra et al., 2011). In a water footprint sustainability assessment, the different components of the water footprint of a product are placed in the context of the sustainability of local water consumption to estimate the extent to which a product's water footprint contributes to local unsustainable water use. However, there are limited studies that use sustainability assessments associated with ruminant production systems. De Miguel et al. (2015) recently used this methodology to analyze the sustainability of the swine sector in Spain using water scarcity and water quality indicators. Hoekstra (2016) argues that the volumetric estimates derived through WFA have environmental relevance besides their benefit as indicators of water use efficiency, because every liter of water consumed reduces the amount of water available for other uses.

Commonalities, Differences, and Complementarities of Water Use Metrics

Comparisons of methods that are used to quantify water use in ruminant production systems are presented in Table 1. The key feature of all available metrics described earlier is freshwater resources (Hoekstra, 2015; Pfister, 2015). The method that is called "conventional" in this paper refers to the quantification of water demand for individual livestock or livestock operations. Although estimating the water requirement in ruminant operations provides useful information for producers and policymakers to match production objectives with water availability, this approach does not typically include indirect water use (e.g., irrigation for feed production, feed processing, transportation) in the supply chain or impacts on water quality (MacKichan, 1951; Maupin et al., 2014).

The LWP and WFA are similar in that inputs are expressed relative to outputs (i.e., productivity/efficiency oriented) for the system under consideration. Compared with LCA, the LWP approach is deemed a more convenient tool for routine use in designing and implementing water use–efficient feeding and animal management strategies (Blümmel et al., 2014). One notable difference between estimates derived using the LWP approach is that outcomes can be expressed in both physical and monetary units, a trait that makes this approach popular among economists. Livestock water productivity can be viewed as the inverse of the water footprint of livestock products: livestock product produced per unit of water consumption vs. water consumed per unit of livestock product.

The key conceptual steps in WFA and LCA are very similar, albeit the terminology is slightly different (Fig. 3). Both methods normally use a "life cycle" approach where the determination of inputs and outputs related to a product or a production system is an aspect of the analysis. Life cycle assessment is an iterative process where interpretation of results at every stage might lead to adjustments in the goal, scope, and subsequent phases. Although it is not apparent from the visual framework, the WFA guidelines also recognize the necessity of iterative phases in water assessment (Hoekstra et al., 2011).

One of the recognized differences between the approaches is that the WFA approach defines water as being blue, green, or gray and attempts to measure both direct and indirect water consumption of individual animals, sectors, and countries. Most LCA studies do not take into account green water, because it is assumed to be addressed by the environmental impact indicators associated with land occupation; this avoids double counting of the same impacts by different impact categories. Green and blue water are given equal importance in WFA (Hoekstra et al., 2011; Hoekstra, 2015). Another important distinction between the WFA and LCA methods is that WFA treats water as a global issue whereas LCA considers water use as a local issue, assuming that there is no global fresh water shortage (Pfister, 2015; Hoekstra, 2016; Pfister et al., 2017). Most WFA and LCA studies also differ in their approach of calculating and communicating water use estimates. Life cycle assessment studies generally use scarcity-weighted water use to compare potential impacts in water-scarce and water-rich areas that are reported as impact equivalents, (i.e., relative impact estimates deemed to reasonably reflect pressure exerted on the water bodies), whereas results from water footprint investigations are normally reported in volumetric units.

In 2014, the International Organization for Standardization (**ISO**) released a document entitled *Environmental Management – Water Footprint – Principles, Requirements and Guidelines* (ISO 14046:2014; ISO, 2014), which defined a WFA as a "compilation and evaluation of the inputs, outputs, and

Table 1. A comparison of methods for quantifying water use in livestock production systems

Metric tool	Description/definition	Benefits and application	Limitations	Sources/examples
Conventional approach	• Operational water demand or requirement (i.e., drinking water, cleaning livestock and facilities, cooling purposes, and animal waste disposal systems) • Demand oriented	• Estimates water consumed or required directly by the ruminant and/or farm • Main (potential) users: producers and policymakers	• Does not normally account for off-farm and indirect water use in the supply chain (e.g., feed production, irrigation, feed processing, transportation) • Water quality is not considered	MacKichan (1951) and Maupin et al. (2014)
Virtual water	• The total volume of fresh water embedded or embodied in a ruminant product • The precursor of a Water Footprint approach	• Describes indirect consumption of water associated with a given ruminant product across the supply chain (i.e., through trade, exports, and imports) • The concept is simple and popular. • Main (potential) users: analysts and policymakers	• Limited spatial or temporal dimension (i.e., does not properly consider where or when the water was used in the production process and, hence, limited measurement of local specific impacts) • Does not differentiate types of water used	Allan (2001), Chapagain and Hoekstra (2003), Hannan (2013), Mazzi et al. (2014), and Altobelli et al. (2016)
Water footprint assessment	• The total volume of consumptive freshwater use and amount of water assumed to be required to dilute pollutants produced during the production process • Identifies different forms of water (i.e., blue, green, and gray) • Treats water as a global issue • Efficiency oriented	• Measures the aggregated direct and indirect water consumption of products, individuals, sectors, and countries • Used for national, regional, and global assessments of ruminant products and productions systems • Popular, because the estimates are relatively easy for users to understand • Main (potential) users: consumers and policymakers.	• Local impacts of water use are given little emphasis • Combining quality-related estimate (gray water) with other components (green and blue) limits the comparability of the aggregated estimate • Very data intensive	Hoekstra et al. (2011), Mekonnen and Hoekstra (2012), and Altobelli et al. (2016)
Livestock water productivity	• The ratio of the net beneficial ruminant-related products and services to the water depleted in producing them • Can be expressed in physical or monetary terms per unit of water used • Indicator of output of a ruminant production system with respect to water as input • Productivity oriented	• Identifies options for more effective and sustainable use of water • Takes into account the multiple benefits of ruminants • Recognizes the importance of competing uses of water while it focuses on livestock–water interactions • Useable at a local (e.g., household, community, watershed, and river basin) scale • Main (potential) users: producers, engineers, economists, and policymakers	• Difficult to quantify and standardize the values of multiple benefits in physical or monetary terms (e.g., draft power, manure, meat, milk, hides) • Does not normally present separate estimates for blue and green water use	Peden et al. (2009), Sharma et al. (2015), and Altobelli et al. (2016).
Life cycle assessment	• Consumptive water use and associated environmental impacts caused by the production, consumption, and disposal of an animal product along the entire value chain • Considers water use as a local issue • The water use is evaluated in relation to local water stress in the area where it is used. • Impact oriented	• Provides results along the entire value chain • Comprehensive, detailed method • Assesses location specific environmental impacts of ruminant water use • Main (potential) users: specialists and enterprises	• Assesses mostly blue water use (i.e., excludes green water use) • Difficult to communicate results to nonspecialists • Very data intensive	Altobelli et al. (2016), Ran et al. (2016), and Pfister et al. (2017).

the potential environmental impacts related to water used or affected by a product, process, or organization" (ISO, 2014, p. 3). Similarly, LCA was defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2014, p. 4). Based on this ISO definition, analysis of the product under investigation throughout its life cycle is mandatory for LCA whereas it is optional for WFA. Furthermore, ISO 14046:2014 (ISO, 2014) does not classify water into the blue, green, and gray categories that are commonly referred to in WFA studies. Although there is ongoing debate regarding the definitions of terms and other aspects associated with the methodologies to estimate water use (Hoekstra, 2016; Pfister et al., 2017), the ISO document serves as a valuable reference be-

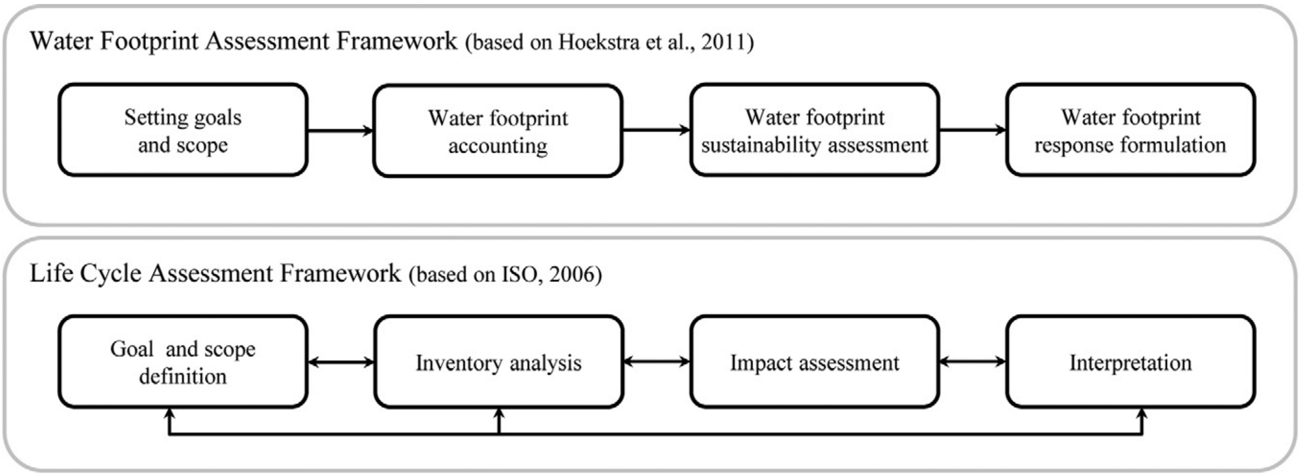

Figure 3. Frameworks of water footprint assessment and life cycle assessment methods. ISO 14040 = ISO 14040:2006 (ISO, 2006).

cause it describes fundamental principles and requirements necessary for such an undertaking.

OTHER METHODOLOGICAL CONSIDERATIONS

Spatial and Temporal Dimensions

The water footprint of a ruminant production system or a product can be estimated at the local, regional, or global scale. Unlike the far-reaching effects of climate change as a result of greenhouse gas emissions, the effects of water mismanagement and scarcity are primarily felt and can be measured in localized watersheds (Zonderland-Thomassen and Ledgard, 2012; Pfister, 2015). Nonetheless, local issues associated with the availability of water may affect the socioeconomic and political stability of a region, resulting in broader impacts. Likewise, global or regional improvements in water resource management may not result in improvements at a local level, making location-specific studies crucial. Water footprint assessments should have the flexibility to be applicable over a range of spatial scales from the household to watershed and global scales. Although LCA is a valuable approach to inform decision makers as well as the public about water-related environmental impacts of ruminant production, extrapolation of this approach to the national or global scale could prove challenging due to data scarcity. Both WFA and LCA approaches consider the importance of temporal differences associated with water use due to uneven inter- and intra-annual distribution of water availability (Pfister, 2015; Hoekstra, 2016).

Bottom-Up versus Top-Down Approaches

Water use assessments can be undertaken using a top-down or bottom-up approach or a combination of the 2 approaches. The top-down approach estimates the water footprint by taking total water use in a country or a region and adding imports while subtracting exports as estimated by an input–output analysis (Mekonnen and Hoekstra, 2012; Chenoweth et al., 2014). The bottom-up approach estimates water use associated with a product or service by collecting detailed data at each stage of the supply chain and aggregating it into regional, national, continental, or global profiles (Chen and Chen, 2013; Chenoweth et al., 2014). For example, if the system boundary is cradle-to-table, data for individual commodities and production processes are aggregated to model the entire production system in a country or region. Although detailed information on the nature of the final food product is an attractive feature of the bottom-up approach, the diversity of food types and their associated inputs makes it difficult to consider the total value of all goods and services on a consistent basis (Chen and Chen, 2013).

After comparing country water use estimates following bottom-up and top-down approaches, Feng et al. (2011) reported that the total water footprint may vary by as much as 48% as a consequence of differences in computational methods. These researchers suggested that hybrid models should be developed so as to take advantages of the strengths of each of the 2 approaches. Scherer and Pfister (2016) used a hybrid approach when investigating water-related resource use of food items including cow milk consumed in Switzerland. The bottom-up approach may be more suitable to capture the water use of detailed agricultural products (e.g., beef), whereas the top-down approach may be more appropriate to estimate water use within broader prod-

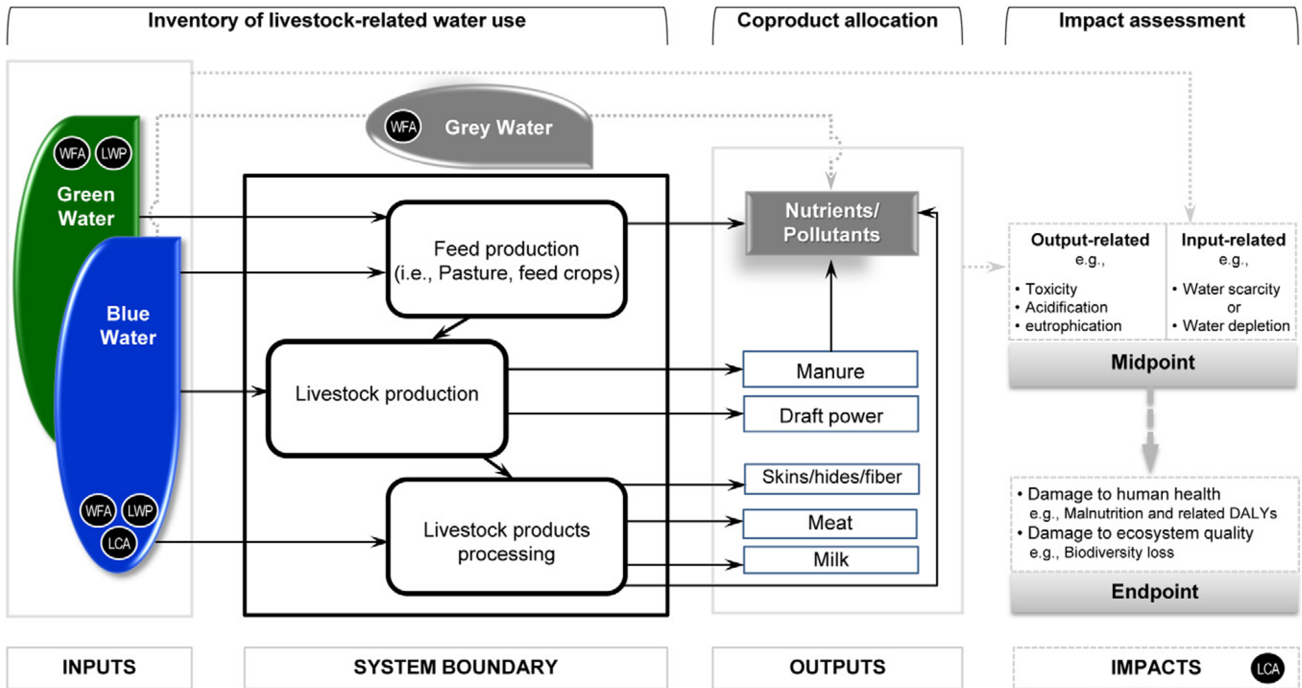

Figure 4. A simplified representation of water use assessment in the context of ruminant production systems. Cradle-to-farm gate refers to all water used to produce a live animal. Cradle-to-processing plant includes water use associated with processing of animal products. Inputs or outcomes commonly included in a specific water use assessment method are tagged in the figure. Livestock water use accounting/inventory analysis is the essential segment of all the methods, but the types of water considered depend on the assessment method and scope of the analysis. All methods take into account water use from surface water and groundwater sources (blue water). Studies based on water footprint assessment (WFA) and livestock water productivity (LWP) typically consider green water. Gray water is an additional feature of WFA, whereas specific pollution impact categories (e.g., eutrophication and toxicity) are also covered in life cycle assessment (LCA). Inventory results and outputs are regularly used to assess midpoint and endpoint impacts in most LCA studies.

uct categories or sectors as a whole (Feng et al., 2011; Chenoweth et al., 2014) such as regional livestock production involving multiple commodities. The reliability and, therefore, the applicability of the estimates derived from both approaches are highly dependent on the quality of data used in the calculations.

System Boundary, Functional Unit, and Coproduct Allocation

Defining the system boundary clearly is one of the key steps in the quantification of water use associated with a ruminant product. The main purpose is to determine which components (unit processes) should be included in the production system under consideration. This decision is primarily dependent on the goal and scope of the study. Similarly, the choice of the functional unit can have a significant effect on the outcome of the water use assessment (Zonderland-Thomassen et al., 2014). The functional unit is a reference measure for quantifying the performance of a product system (ISO 14040:2006; ISO, 2006) and enables the comparison of different production systems. Ruminant products are often measured in weight (e.g., marketable LW of an animal, carcass weight, boneless meat weight) or volume (e.g., L or m^3 of milk). The water use estimates of ruminant products are commonly expressed in water volume (e.g., L or m^3) per unit product reflecting the major output of the system under consideration (e.g., L H_2O/kg LW [Ridoutt et al., 2011, 2012], L H_2O-eq/kg LW [Ridoutt et al., 2012; Zonderland-Thomassen et al., 2014], L H_2O/kg meat [Beckett and Oltjen, 1993; Capper, 2011]) or compared as a ratio of output to input (e.g., \$US/m^3 H_2O, kg product/L H_2O). The estimates can also be expressed in terms of quality metrics such as protein content. For instance, Mekonnen and Hoekstra (2012) have translated water footprints in liters H_2O per kilogram meat or milk into water footprints in liters H_2O per kilocalories and in liters H_2O per gram of protein to enable comparison of water efficiency with other food products.

Coproduct allocation, which refers to the partitioning of water use to the various products (e.g., meat, milk, fiber, skin) of the livestock or crop–livestock systems, is an important aspect of water use assessment and can be performed in different ways, most commonly either by the biological function or economic value. In LCA, there is a long history of discussing alternative allocation methods, a topic that is still widely debated (Wernet et al., 2016). However, most generic data are allocated based on economic value.

A simplified schematic representation of the main components of water use quantification relating to ruminant production systems is illustrated in Fig. 4.

Table 2. Summary of the water use values associated with beef, milk, and sheep meat production from water footprint assessment–based studies

Product	Functional unit[1]	Region/ country	Estimate Blue	Green	Gray	Aggregate	Source
Beef	L H_2O/kg	Global	550	14,414	451	15,415	Mekonnen and Hoekstra (2012)
	L H_2O/kg	United States	525	12,933	733	14,191	Mekonnen and Hoekstra (2012)
	L H_2O/kg	Global	–	–	–	15,497	Hoekstra and Chapagain (2007)
	L H_2O/kg	United States	–	–	–	13,193	Hoekstra and Chapagain (2007)
	L H_2O/kg	England	67	14,900	2,690	17,657	EBLEX (2010)
Milk	L H_2O/kg	Global	86	863	72	1,020	Mekonnen and Hoekstra (2012)
	L H_2O/kg	United States	60	647	89	796	Mekonnen and Hoekstra (2012)
	L H_2O/kg	Global	–	–	–	990	Hoekstra and Chapagain (2007)
	L H_2O/kg	United States	–	–	–	695	Hoekstra and Chapagain (2007)
	L H_2O/kg FPCM[2]	New Zealand	–	–	–	945 and 1,084	Zonderland-Thomassen and Ledgard (2012)[3]
	L/kg ECM[4]	Global	121	1,466	106		Sultana et al. (2014)
	L H_2O/kg	Germany	3.94	–	–	–	Drastig et al. (2010)
Sheep meat	L H_2O/kg	Global	522	9,813	76	10,412	Mekonnen and Hoekstra (2012)
	L H_2O/kg	United States	315	10,948	44	11,307	Mekonnen and Hoekstra (2012)
	L H_2O/kg	Global	–	–	–	6,143	Hoekstra and Chapagain (2007)
	L H_2O/kg	United States	–	–	–	5,977	Hoekstra and Chapagain (2007)
	L H_2O/kg LW[5]	Chile	193	6,034	151	6,378	Toro-Mujica et al. (2016)
	L H_2O/kg	England	49	55,800	1,910	57,759	EBLEX (2010)[6]

[1]Unless specified, the functional unit is a kilogram of the respective product.

[2]FPCM = fat–protein–corrected milk.

[3]Investigated dairy operations in 2 contrasting regions.

[4]ECM = energy-corrected milk.

[5]LW = live weight.

[6]Green water estimate in this study includes rainfall used to produce all feed crop biomass (including pasture) at the place where it falls.

The commonly used boundaries in these systems are cradle-to-farm gate, cradle-to-processing plant, and cradle-to-table. Cradle-to-farm gate refers to all water use processes required to produce a live animal or a product from a live animal (e.g., milk) that is ready for transport to a slaughterhouse or fresh-product processing plant. Cradle-to-processing plant covers the water use associated with processing of ruminant products as well. Cradle-to-table further takes into account water use at the retail and consumer level. Given the complexity and the diversity of animal-origin commodities and the impracticality of finding adequate water use data from retailers and individual households, the first 2 system boundaries are most frequently used. The framework also shows the potential entry points of nutrients or other pollutants into blue water sources during feed production (e.g., fertilizers and pesticides), ruminant production (e.g., manure), and product processing (Fig. 4). In sustainable production systems, manure can play a key role in improving soil fertility and crop production. Use of manure as an organic fertilizer reduces the need for chemical fertilizers and the energy associated with their production. In cases where the flow of ruminant production–related nutrients and pollutants into water bodies is minimal, this factor may be excluded from the analysis. However, when ruminant production introduces nutrients (e.g., N, P) and other pollutants (e.g., pesticides) into blue water that can pose adverse effects to the health of ecosystems and humans, the inclusion of indicators that include this impact may be appropriate. Some impacts may possibly be related to the withdrawal of water from water sources such as surface water and groundwater for ruminant or feed production (i.e., input-related impacts). Environmental impacts such as acidification, eutrophication, and toxicity are generally output related as opposed to input related and are considered in impact assessment of pollutants in both LCA and WFA methodologies.

COMPARISON OF RUMINANT WATER USE ESTIMATES

Water use values associated with beef, milk, and sheep meat production reported in various studies are presented in Table 2 (WFA) and Table 3 (LCA, LWP, and others). The variation in water use estimates reflects differences in methods, assumptions, and scale of the analysis as well as functional units used. Water use estimates from LCA studies are generally lower than

Table 3. A comparison of water use values associated with beef, milk, and sheep meat production from various life cycle assessment (LCA), livestock water productivity (LWP), and other studies

Product	Functional unit	Estimate	Region/country	Approach	Source
Beef	kg meat/L water	11,500	Ethiopia	LWP	Gebreselassie et al. (2009)
	L H_2O/kg HSCW[1]	18–540	Australia	Hybrid LCA	Peters et al. (2010)
	L H_2O-eq/kg LW[2]	3.3–221	Australia	LCA	Ridoutt et al. (2011)
	L H_2O/kg LW	24.7–234	Australia	LCA	Ridoutt et al. (2012)
	L H_2O/kg LW	9,818–12,855	Australia	LCA	Eady et al. (2011)
	L H_2O-eq/kg LW	0.37	New Zealand	LCA	Zonderland-Thomassen et al. (2014)
	L H_2O-eq/kg beef	15.1–20.0	United Kingdom	LCA	Zonderland-Thomassen et al. (2014)
	L H_2O/kg beef carcass	1,763	United States		Capper (2011)
	L H_2O/kg beef	43,000	United States		Pimentel et al. (2004)
	L H_2O/kg beef	105,400	United States		Pimentel et al. (1997)
	L H_2O/kg boneless beef	3,682	United States		Beckett and Oltjen (1993)
	L H_2O/kg beef	200,000	United States		Thomas (1987)
Milk	L H_2O/kg	1,000	Ethiopia	LWP	Gebreselassie et al. (2009)
	L H_2O/kg of TMSW[3]	108.0	Australia	LCA	Ridoutt et al. (2010)
	L H_2O/kg of TMSS[4]	15.8	Australia	LCA	Ridoutt et al. (2010)
	L H_2O-eq/kg of TMSW	14.4	Australia	LCA	Ridoutt et al. (2010)
	L H_2O-eq/kg FPCM[5]	0.011–11.1	New Zealand	LCA	Zonderland-Thomassen and Ledgard (2012)
	L H_2O/kg FPCM	66	The Netherlands	LCA	De Boer et al. (2013)
	L H_2O-eq/kg FPCM	11	China	LCA	Huang et al. (2014)
	L H_2O-eq/kg FPCM	461	California, United States	LCA	Huang et al. (2014)
	L H_2O-eq/kg FPCM	0.01	New Zealand	LCA	Huang et al. (2014)
	kg (FCM[6])/m^3	1.0–1.7	Germany	LWP	Krauß et al. (2015)
Sheep meat	L H_2O-eq/kg meat	0.26	New Zealand	LCA	Zonderland-Thomassen et al. (2014)
	L H_2O/kg LW	58.1–238.9	Australia	LCA	Wiedemann et al. (2016)
	L H_2O-eq/kg meat	8.4–23.1	United Kingdom	LCA	Zonderland-Thomassen et al. (2014)

[1]HSCW = hot standard carcass weight.

[2]H_2O-eq = water equivalent; LW = live weight.

[3]TMSW = total milk solids in whole milk.

[4]TMSS = total milk solids in skim milk.

[5]FPCM = fat–protein–corrected milk.

[6]FCM = fat corrected milk.

those obtained using WFA. This reflects the exclusion of green and gray water from the former approach and discounting of blue water based on local water scarcity. After assessing the water footprint of New Zealand dairy farming in nonirrigated moderate rainfall and irrigated low-rainfall regions, Zonderland-Thomassen and Ledgard (2012) observed notable variation in final estimates due to inherent differences in assumptions, type of water included (i.e., inclusion or exclusion of green/gray waters), and data normalization procedures between LCA and WFA. However, data collected during the inventory stage were almost identical between the 2 methods. There are regional differences in the consumptive water use associated with livestock products (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013; Sultana et al., 2015) as a consequence of differences in production systems and their productivity. Sultana et al. (2015) reported values for water use per unit of energy-corrected milk in Africa and Asia that were about 3 times greater than in North America, reflecting differences in milk yield and feeding systems.

Some of the earlier attempts to approximate water use per product resulted in values that were considerably greater than recent estimates (Thomas, 1987; Pimentel et al., 1997). As the methodology used was not fully described, it is difficult to explain these exceptionally high values. However, allocation of all the water use on pasturelands to animal products may be one of the factors that contributed to inflated estimates. Recent estimates obtained using the WFA approach for beef (Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2012) are lower than earlier reports (Thomas, 1987; Pimentel et al., 1997) but greater than those obtained using LCA (Ridoutt et al., 2012). Although WFA includes evaporation related only to that portion of the pasture that is consumed (not total ET from pasturelands), the inclusion of green water leads to higher estimates.

OVERVIEW OF STRATEGIES TO REDUCE THE WATER USE OF RUMINANT PRODUCTS

Changing Consumption Patterns

Mekonnen and Hoekstra (2012) reported that, with the exception of butter, the water footprint of any food of animal origin is larger than the water footprint of an equivalent amount of food from plants (expressed as liters per unit product or per kcal). Based on the reported higher water use estimates of livestock production and products, one of the most common strategies proposed to lower water use is to reduce the consumption of foods of animal origin (Hoekstra, 2012; Mekonnen and Hoekstra, 2012; Vanham et al., 2013). Another related recommendation aimed at consumers is to select livestock products based on their water footprint (Ercin et al., 2012). Because of differences in feed conversion efficiencies, water use per kilogram is generally greater for beef than for chicken or pork (Gerbens-Leenes et al., 2013). However, the methodology used does not account for local water scarcity and other ecological and socioeconomic factors (Wichelns, 2015; Atzori et al., 2016). Damerau et al. (2016) explored a set of possible changes in consumption patterns in the agricultural and energy sector to determine the indirect impact these trends might have on global water requirements until 2050. In some food production scenarios, plant protein sources were shown to require more water than animal protein sources. For instance, in the Middle East and Africa, animal protein from goats would require considerably less water than a maize/pea mix (Damerau et al., 2016). There may be specific cases and regions where dietary adjustments may help mitigate environmental impacts and potential human health risks. A possible reduction in meat consumption per person in developed countries may be recommended to reduce risk of heart disease and some types of cancer (McMichael et al., 2007; Herrero and Thornton, 2013). But blanket recommendations to avoid animal-origin products do not consider that ruminants are the mainstay of millions of smallholder farmers throughout the world and that the products are among the highest-quality protein sources available in many regions of the world (Mekonnen and Hoekstra, 2012). General recommendations across all regions are also misleading, as some producers or regions raise livestock more efficiently than others. Large numbers of livestock producers, specifically those who manage ruminants, are not only practicing husbandry but are also stewards of the vast grazing lands that provide a range of ecosystem services including enhancing biodiversity and carbon sequestration (Guyader et al., 2016). In some regions of the world such as the arid areas of sub-Saharan Africa, ruminant production is the only sustainable agricultural activity due to climatic, soil-related, and socioeconomic factors. Failure to acknowledge this reality may lead to unsustainable and counterproductive outcomes.

Laboratory cultured meat is also being touted as a potential competitor to conventionally produced meat in the future, assuming that meat produced in vitro uses less water and energy (FAO, 2011). After estimating the potential environmental impacts of large-scale cultured meat production compared with conventionally produced European meat products, Tuomisto and Teixeira de Mattos (2011) reported that artificial meat used 82 to 96% less water. According to Mattick et al. (2015), although artificial meat could require less land and agricultural inputs than livestock products, energy use would be more intensive due to the replacement of biological functions with industrial equivalents. Even so, the consumer acceptance of cultured meat products remains unknown and as a result such production is unlikely to be marketable in the near future (Hocquette, 2016).

Increasing Water Use Efficiency

Many strategies have been reported to increase the water efficiency of ruminant production. These strategies may be broadly categorized into those that are related to feed production/utilization, best water management practices, and animal production efficiency–related strategies. Although access to adequate drinking water is critical for any livestock operation, about 100 times more water is estimated to be used in feed production compared with drinking (Gerbens-Leenes et al., 2013; Blümmel et al., 2014). Increasing ruminant water use efficiency with regards to feed production and utilization may be achieved through enhancing crop productivity (yield per hectare; Capper, 2011), selecting and breeding crops and forages for water use efficiency (Blümmel et al., 2014), and increasing the use of crop byproducts and residues (Peden et al., 2007; Descheemaeker et al., 2010). Moreover, developing and adopting water conservation management practices has a direct impact on the water demand of feed and forage crops (Beckett and Oltjen, 1993; Peden et al., 2007). Jägermeyr et al. (2016) recently simulated the yield-increasing potential of irrigation water productivity under the current and projected future climate scenarios. They showed that irrigation efficiency improvements could save up to 48% of the global nonproductive water consumption. Other water conservation measures that can enhance water use efficiency include mulching, cover crops, minimum or zero tillage, and adoption of alternate drought-tolerant crops (Evans and Sadler, 2008; Keesstra et al., 2016). In the Midwestern United States, Basche et al. (2016) showed that a cover crop enhanced the field capacity water content and plant available water by 10 to 11% and by 21 to 22%, respectively. Compared with conventional tillage, implementation of improved tillage in Ethiopian agricultural systems led to over a 50% reduction in surface runoff and a 9 to 40% improvement in water productivity (Asmamaw, 2016).

A number of studies showed that improvement in the production efficiency of livestock has a positive effect on water use efficiency (Gebreselassie et al., 2009; Peden et al., 2009; Capper, 2011; Krauß et al., 2015). This is partly attributable to lower share of water for maintenance purposes due to the need to raise fewer animals to produce a given amount of product (Peden et al., 2009), an outcome referred to as "dilution of maintenance." After comparing various production scenarios, White (2016) reported that improving protein and energy use efficiency of dairy cattle would be a reasonable option to reduce water use without negative implications for profitability. However, considering that ruminants are kept in many regions of the world to make use of available feed and grazing resources, optimizing production efficiency may not always be practical.

OPPORTUNITIES AND CHALLENGES IN WATER USE ACCOUNTING

The metrics of WFA and LCA used to quantify the water use of ruminant products are rapidly evolving, making it challenging to compare water use among studies. Even though refining the specific methods is expected to enhance the accuracy of estimates, using similar terminologies while presenting divergent or conflicting results may confer contradicting information on the same issue to the public. There were some attempts made by LCA and WFA communities to discuss and find complementarities between the 2 approaches, but those efforts have not yet led to unified methods (Boulay et al., 2013; Pfister and Ridoutt, 2014; Hoekstra, 2016; Pfister et al., 2017).

Peters et al. (2010) stated that calculating all water inputs to ruminant production in WFA may be useful to inform economic policy (e.g., determining if a nation is maximizing financial gain) whereas it may well be inappropriate to include green water if the focus is mitigating environmental burdens. One big challenge in the process of standardizing water use metrics will be finding common ground to avoid either oversimplification or oversophistication of the information generated. For WFA, aggregating different types (colors) of waters into one value may lessen its practical use (Zonderland-Thomassen and Ledgard, 2012). The stand-alone option in H_2O-eq proposed by Ridoutt and Pfister (2013) for LCA, which incorporates both consumptive and degradative water, has also been challenged due to difficulties in verification or interpretation in any physical way (Hoekstra, 2016). Finding common ground in terminology and reporting is, therefore, a key challenge and opportunity for effective communication of results to the general public and decision makers.

The details and relevance of water-use calculations and, thereby, final outputs are determined by not only the metrics selected but also the availability and quality of data. For cradle-to-farm gate or cradle-to-table water use assessments, it is usual to rely on generic data for modeling the supply chain. Due to the high variability of performance in livestock production even among producers in the same region, such generic data typically add more uncertainty than in assessments of industrial processes, where variability is generally lower. Appropriate allocation of water use estimates to various ruminant products is an immense task that calls for more investigation in a local context. This may involve well-defined apportioning of input and output parameters among products (e.g., meat and milk) among species and products in multispecies ruminant production systems and between crop and livestock sectors. The latter also includes the use of an important byproduct, manure, which, depending on circumstances, can be considered a waste product or an essential input into crop production systems.

The exclusion of the green water from the LCA perspective water use has been increasingly viewed as a flaw for several reasons, including that 1) the final estimates may not properly reflect actual water efficiency in livestock production in view of competing uses (Ran et al., 2016) and 2) it disregards the observation that green water can also be a scarce resource (Hoekstra, 2016). Although green water scarcity can be assessed through the impacts of land use in LCA, it does not clearly reflect water use efficiency. Núñez et al. (2013) proposed a framework to include green water in LCA by taking into account the net change in the ET of the production system compared with the natural reference situation. Atzori et al. (2016) recently compared the water use estimates derived using the current WFA approach with those estimated with an alternative method that they called net water footprint. In this exercise, they included a portion of green water in their analysis, but not the total amount. Their justification was that although ET of pastures and feed crops appears to be the main form of water loss, it also occurs in natural ecosystems or in the absence of ruminant production (Atzori et al., 2016), following the approach of Núñez et al. (2013). They considered differential ET between the total ET of pasture or feed crop and the ET of a hypothetical scenario of a natural cover. The values obtained for meat and milk in Mediterranean conditions using net water footprint were lower than those estimated using standard WFA (Atzori et al., 2016). According to Hoekstra et al. (2011), net green water footprint refers to reduced blue water runoff and, therefore, is a blue water footprint because it reflects reduced runoff as a result of increased ET, implying that green water consumption may well still be overlooked. In addition, the difference between the ET of grazing land or cropland and the ET of natural vegetation is generally negative, implying that farmlands increase rather than reduce runoff (Hoekstra, 2016).

Rain in natural ecosystems is generally renewable, not diverted from its original source, and cannot be consumed faster than it falls (Peters et al., 2010). Therefore, counting green water use in natural ecosystems used for ruminant production (i.e., rangelands), which are mostly marginal lands with limited alternative use, may bring about inflated and misleading estimates of water use. Whether or not the water use assessment makes allowances for green water, the analysis must be based on ET associated with the actual portion of the pasture that the animal consumes. Moreover, the green and blue water consumption should be reported separately.

IMPLICATIONS FOR POLICIES AND TRADE

More than half of the people in the world who are defined as poor are dependent on livestock production (Thornton et al., 2002; Thomas and Rangnekar, 2004). In addition to the provision of food, clothing, and draft power, ruminants serve as a source of income for many of these people. Ruminant producers are not only practitioners of animal husbandry but also the stewards of vast tracts of tame and native pasturelands. Many rangelands are not suitable for any agricultural activity other than ruminant production due to low and erratic precipitation, steep topography, poor drainage, or low soil fertility (Squires, 2010). Ruminants and grasslands have multiple benefits, although it is challenging to quantify their social value and environmental (e.g., ecosystem services) contributions in monetary or quantitative terms. Development activities aimed at sustainable water use in ruminant production should have both a quantitative and a qualitative value for these contributions (Herrero et al., 2015).

The adoption of labeling water use estimates of livestock and other food products to enable consumers to compare environmental impacts of food products has been suggested (Galli et al., 2012; Hoekstra, 2015; Leach et al., 2016). According to Wichelns (2015), water use estimates derived using virtual water approaches might not provide reliable information to assist policymakers, industries, or consumers in making appropriate decisions as opportunity costs, water scarcity conditions, socioeconomic implications, and other water use–related benefits are often not considered. Therefore, appreciating the complexity of food production systems and associated trade-offs is necessary to prevent unintended harm to communities and the environment (Herrero et al., 2015). Including the sustainability of the water footprint of products as a criterion in multiple-criteria environmental labeling schemes may be a way forward.

In countries and regions where there is severe water scarcity, policymakers may consider importing commodities from water-rich areas. However, socioeconomic, cultural, and political implications of these options and policies must be carefully weighed (Herrero et al., 2015). The comparative advantage and opportunity costs of the commodities should also be considered. Total dependence on other regions or countries for food products is likely to become a serious problem as their supply and price could be heavily influenced by external factors that could threaten food security. Such instances may foster risks of internal or external political instabilities and conflicts. In regions with growing human populations, reducing population growth rate must be an inevitable component in the water use and other environmental policies of governments because it is a major driving force of all human activities including ruminant production. Unless the growth of human population is curtailed, strategies to reduce water use per unit product will continue to be equally or more important than reducing total water use.

CONCLUSIONS

This review outlines different methods available for quantifying water use associated with ruminant products and productions systems. The most common methods are WFA and LCA, which continue to evolve and offer different perspectives with regard to water use. The rapid change in water use methodology creates a challenge for researchers and other stakeholders to stay current and compare findings arising from different studies. The major challenge is finding a balance between the demands of comprehensiveness and simplicity to generate a meaningful yet practical water use assessment.

There are vast discrepancies in the reported water use estimates for ruminant products, which are partly attributable to differences in production systems as well as forms of water considered in the analysis. One of the clear messages from the literature is that ruminant species and ruminant production systems differ in the amount of water required per animal or animal product. Blanket recommendations that ignore these differences may not only be misleading but could prove counterproductive to the efforts of accurately assessing water use. Meat from ruminants appears to have relatively higher water use estimates. Given that ruminants often use feed resources that are unsuitable as food and mainly use water that has zero or small opportunity cost, the magnitude of the reported estimates may not always mirror actual impacts.

Because feed production accounts for the greatest part of water use in ruminant production, future research to improve water productivity should particularly focus on this area. Feed and pasture production management strategies targeting efficient use of both rain and irrigation water will play a role in reducing the water footprint of ruminant products because they increase the portion of nonirrigated feed production. Improved management strategies that enhance feed conversion efficiency, growth rate, and carcass weight in ruminants will also reduce water use per unit of meat or milk. Lastly, to use water use estimates for decision-making in the future, further investigation and debate is required to scrutinize the validity of assumptions, the availability and quality of data, and possible trade-offs between other sustainability indicators such as carbon footprint and ecosystem services.

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