ASAS-CSAS ANNUAL MEETING SYMPOSIUM ON WATER USE EFFICIENCY AT THE FORAGE-ANIMAL INTERFACE: Life cycle assessment of forage-based livestock production systems

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ABSTRACT: Livestock production is increasingly subjected to environmental and economic challenges related to water quantities being utilized, expressed as green (evapotranspiration from rain-water), blue (surface and groundwater), or gray (waste) water footprints at each stage of the product life cycle. Published data indicated that the largest share of water being used for producing beef in the United States can be traced back to growing forage and feed (>90%), whereby the green water footprint was substantially greater (12,933 liters of water per kg of product) than the blue water footprint, as only a small amount of pasture- and cropland is irrigated (525 L/kg). Based on prevailing quantification methods, feed conversion ratios, and grazing land required, water footprints for beef produced through grazing alone can be relatively high. Green water footprints can easily reach more than 19,000 L/kg for beef from grazing compared with a maximum of 1,731 L/kg for chicken under a typical scenario. However, much of the existing grazing land cannot or should not be converted to cropland for various ecological reasons,

and large water footprints would remain for the vegetation even if cattle were removed. Life cycle assessments (LCA) were historically developed to provide a framework for evaluation of the full life cycle of a product or service and to ultimately model environmental impacts through life cycle impact assessment methods. Life cycle assessments grew more refined during past years and efforts are being made to reflect the environmental and economic consequences of different livestock and crop production systems more accurately than in the past. Typical beef production systems on natural and naturalized grasslands in North America generate environmental, economic, and societal benefits that should be reflected in future LCA, farm policies, and regulations. To increase the water use efficiency of each segment of the beef supply chain and thereby to reduce water footprints, grazing systems and methods as well as external inputs should be further optimized and integrated toward enhanced ecosystem services, thereby lowering the overall environmental impact of livestock production.

Key words: forage-based livestock production, life cycle assessment, water use efficiency

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INTRODUCTION

Life cycle sustainability assessments seek to quantify environmental, social, and economic

impacts resulting from producing goods and services, utilization over their life span, and ultimately their disposal. In the livestock industry, life cycle assessments (LCA) have primarily been used to estimate environmental “footprints,” either based on carbon dioxide emission equivalents (CO₂-e), or the accumulative water use for a specific marketable product for either the entire length of the product cycle or parts

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of it. The beef industry in particular has been under pressure to assess its natural resource use as regulatory requirements and increased consumer scrutiny requires ever-increasing production efficiency while minimizing negative environmental impacts.

This paper is based on a presentation given at the symposium on “Water use efficiency at the forage-animal interface” during the ASAS-CSAS annual meeting in Vancouver, BC, 2018. The intent of this symposium was to bring speakers from forage and animal science backgrounds together to offer solutions for achieving greater water use efficiency (WUE) in livestock production systems. With the likelihood of increased climate variability, availability of water for forage production will likely become an issue for most parts of the United States, including eastern states which currently have sufficient average precipitation to sustain cattle operations without irrigation.

Although the concept of LCA is not limited to climate impacts, the vast majority of published studies concerning the beef industry refer to CO₂ or other gaseous emissions balances. There is, however, a link between the framework of an LCA and the concept of water footprints. The latter, when expressed as an LCA, offer insight into partial or full supply chain impacts on water resources for a specific product output or management practice. At the same time, water footprints give an indication of WUE, either based on dry matter (DM) production, or in a wider sense based on WUE across field scales or landscape levels. In this paper we will summarize the presentation given at the symposium, and we also will explore basic concepts of LCA and water footprints, show linkages between the two, and lay out challenges and opportunities for more efficient water use in forage-based livestock production systems.

LIFE CYCLE ASSESSMENTS—BASIC CONCEPTS

Life cycle assessments seek to quantify the impacts of producing goods on an ecological, economical, and societal scale. Consumers and retailers seek information on the sustainability of a product and the resource use efficiency of a particular product. The first examples of partial LCA can be traced back to the 1960s and 1970s, during which some enterprises, including the Coca Cola company, conducted studies on resource requirements and emission loadings for beverage containers. The decade between 1990 and 2000 was a period during which LCA became more standardized and that led

to an increase in the number of published articles and manuals (Guinée et al., 2011). During the past 2 decades, the Society of Environmental Toxicology and Chemistry as well as the International Organization for Standardization (ISO) were both instrumental in developing methods and procedures for LCA studies. More recently, LCA were broadened in their objectives away from a purely mechanistic point of view to analyses that encompass various layers of society, supply chain, and product sustainability (Guinée et al., 2011).

Life cycle assessments can be divided into attributional and consequential LCA. As the terms imply, the former ones are concerned with inputs and outputs attributable to a functional unit, while the latter estimates the consequences associated with a change in demand for the functional unit. Predicting consequences of production processes is arguably more important than more traditional attributional LCA, as consequential LCA allows feedback mechanisms for assessing the long-term sustainability for a given output or functional unit. Consequential LCA gives consumers the ability to choose product A over B and is capable of assessing preferences for new technologies and processes (Rebitzer et al., 2004; Thomassen et al., 2008).

Before an LCA is initiated, goals and scope of the study will be defined which includes setting product system boundaries, evaluating data requirements, and identifying the target audience for the end results (ISO, 1997). Figure 1 provides an overview of the LCA framework. Based on the scope of the LCA, the functional unit will be set to describe the product output that will be investigated, e.g., before-mentioned CO₂-e emitted per kg of beef produced or per live animal out of the farm gate. Identifying the appropriate functional unit requires setting carefully the product system boundaries before conducting the LCA.

The Building Blocks of an LCA

The connecting pieces of each LCA are single process steps which encase and describe inputs and outputs to and from the environment during each of these steps. Those steps are then connected and related to other process steps to create LCA diagrams that visualize production flows and ultimately the final impact to the environment from producing the functional unit. Single processes can encompass, for example, steps such as the feedlot phase in beef finishing, or pasturing calves until weaning and the emissions or other footprints associated with it. For the purpose of collecting

Figure 1. The components of a life cycle assessment as laid out and specified by the International Organization for Standardization (adapted from ISO, 1997).

information for an LCA, large amounts of data must be compiled before being used in a study. This requires modeling which is facilitated by tools such as the Integrated Farm System Model (Rotz et al., 2018), and is being widely used to simulate data for processes that are difficult to measure directly for incorporation in LCA. Figure 2 provides an illustration of an LCA network in SimaPro that was included in the presentation.

LIFE CYCLE ASSESSMENTS AND WATER FOOTPRINTS

The concept of the “water footprint” is similar to that of an LCA. In principle, water footprints were developed to assess the impact on a water source from producing, using, and disposing goods and services (Hoekstra et al., 2011). Similar to an LCA, a functional unit will be defined for which a water footprint is established to gauge environmental impacts from using a specific amount of water (e.g., 150 liters for the production per kg of live weight of pork at the farm gate). Expression in this format also requires establishment of goal and scope, inventory analyses, and impact assessments which are all similar to the LCA framework.

The source of water for water footprint assessments is divided into green, blue, and gray water. The definitions and methods were detailed by Hoekstra et al. (2003) and we also refer the reader to the Water Footprint Manual, also published by Hoekstra et al. (2011). Briefly, green water is defined as the consumption of water derived through evapotranspiration from the root zone originating from precipitation, while blue water is derived from groundwater and surface water through irrigation. Gray water refers to the quantity of water necessary to dilute water impaired during the production process to a level meeting regulatory requirements

for a particular contaminant. Figure 3 provides an illustration of green and blue water in a spatial context. We excluded gray water here as this category may be of less importance in forage-based livestock systems, although we recognize that water quality impairments may occur under some circumstances.

The concept of water footprints is relatively recent (Hoekstra, 2003). This is probably because the driving forces behind water footprint analyses and methodologies were a relatively small group of scientists who were instrumental in developing those concepts. Their focus has been squarely placed on water resources only, while LCA describe and refer to a multitude of impact factors, such as emission equivalents, use of specific material resources, or time to finish a certain product, etc. Although the methodologies and calculation processes are essentially the same with the goal of assessing an environmental impact, water footprints are generally published only keeping the water use in mind, while LCA are more frequently used to evaluate more dimensions of environmental concern than simply water.

Water Footprint Values

There is a string of published water footprint reports available with reference to livestock products, crop products, and vegetables (Pimentel et al., 2004; Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2012; Hoekstra, 2015). According to data compiled by Mekonnen and Hoekstra (2012), the water footprint of beef is larger than the water footprint for many crop products based on weight, but smaller per unit of nutritional value (liters of water per g protein) than fruits and nuts.

Values displayed in Table 1 were deliberately chosen for the symposium as those seemingly

Figure 2. This diagram shows a typical SimaPro network output that was used as illustration in the presentation. Results shown here are based on data generated from the USDA/Meat Animal Research Center in Clay City, NE. Each process step shows its own contribution, in this case $\text{CO}_2\text{-e}$, to the final output; likewise, the thickness of the connectors expresses the relative contribution to the final result, in this case $12.2 \text{ kg CO}_2\text{-e/kg}$ of beef, live weight at the farm gate.

Figure 3. Water footprint components and how they relate spatially to each other. The gray water footprint is excluded here for simplicity (adapted from Hoekstra et al., 2011).

present a dilemma for the livestock industry as these values support the assumption that livestock production is generally a wasteful endeavor. However, those numbers were chosen as a backdrop for a detailed explanation of how those water footprint numbers relate to the varied forms of forage-based husbandry, ecological considerations, and if those footprint values can actually be reduced through agronomic or other measures. Striking are the large water footprints resulting from grazing and the impact on green water compared with blue water (Table 1). For example, the production of 1 kg carcass-yield beef produced in the United States requires about 19,000 liters of green water. The blue water footprint for the same category is very small in comparison, only about 525 liters.

The large numbers for green water usage in forage-based beef production are simply evidence for the large amounts of precipitation needed to sustain pastures and produce DM yields sufficiently large to support beef cattle production. The vast majority of water that is being taken up by plants moves through the xylem tissue for cooling purposes and leaves the stomata as water vapor for the exchange with CO₂ (Kramer and Boyer, 1995). Feed:gain ratios (kg DM intake/kg gain) for pasture can be >10 for cattle (Waghorn and Hegarty, 2011), so the overall amount of water that is necessary to support ruminant livestock per unit area is very large by default in forage-based systems.

It should be noted that even if cattle were completely absent, roughly the same amount of water would be moved through the pasture ecosystem to support vegetative growth. This is the reason why we will argue for considering ecosystem services beyond pasture meat production when forage-based systems are evaluated regarding their environmental impacts. In many instances grassland biomes are well adapted to their specific geographic location, so a conversion to cropland may not be advisable from an ecological perspective, even if water footprints would be smaller for the edible plant products cultivated there. In the United States, only 3% of the total cropland is classified as “cropland

pasture” that is converted into pasture and back for crop rotation (Bigelow and Borchers, 2017). Given the geography and topography of grasslands in the United States, it is unlikely that large portions of the current pastureland could be converted to cropland without severe environmental impacts, such as increased soil erosion and runoff. The ecological value of pastureland should, therefore, find its way into LCA and water footprints should be compared in the context of the environmental impact of changing land use.

Of interest are also the water footprints per unit of nutritional value for a specific food item. We adapted data from Mekonnen and Hoekstra (2012) and displayed selected values in Table 2. Due to the high feed conversion ratios for ruminant livestock, the amount of water needed to produce a calorie of beef is more than 3 times larger than for a calorie of chicken meat, and about 20 times than for cereals. The energy density (metabolizable energy) for beef (1,513 kcal/kg) is lower than for many other plant and animal products, including pork (2,786 kcal/kg), but it is difficult to argue for consuming only the highest nutrient-dense products as human nutritional requirements include not just high-caloric food. Another interesting observation is the amount of water required to produce a unit of protein. Fruits require higher amounts of water (180 L/g) than all other products listed in Table 2 including beef (112 L/g). Fruits are certainly not consumed for large protein intake, but it shows that the different food categories all have their specific function within a human diet and cannot easily be substituted with each other just based on water consumption and water footprints during their production cycle.

Arguments laid out previously here showed that water footprints for beef produced from grazing are large and may account for more than 90% of the overall water use. In forage-based systems, as virtually all cow-calf operations are in the United States, ways to reduce water consumption (i.e., increase WUE at the various stages of the life cycle) are explained in the following.

Table 1. Water footprints (green, blue, and gray water) of selected meat products from grazing (liters of water/kg of meat, carcass yield) China, India, and United States

Meat item	China			India			United States		
	Green	Blue	Gray	Green	Blue	Gray	Green	Blue	Gray
Beef (L/kg)	16,140	213	0	25,913	242	0	19,102	525	590
Sheep (L/kg)	9,606	388	0	11,441	489	0	11,910	312	18
Goat (L/kg)	5,073	272	0	8,081	374	0	0	0	0

Gray water footprints were included for U.S. data but were not available for the other 2 countries. Adapted from Mekonnen and Hoekstra (2012).

Table 2. Water footprints for selected food product, per unit of weight and per unit of nutritional value, including the overall nutritional content of each food item displayed

Food item	Water footprint per unit of weight			Nutritional content			Water footprint per unit of nutritional value		
	Green (L/kg)	Blue (L/kg)	Gray (L/kg)	Calorie (kcal/kg)	Protein (g/kg)	Fat (g/kg)	Calorie (L/kcal)	Protein (L/g)	Fat (L/g)
Vegetables	194	43	85	240	12	2.1	1.34	26	154
Nuts	7,016	1,367	680	2,500	65	193	3.63	139	47
Fruits	726	147	89	460	5.3	2.8	2.09	180	348
Milk	863	86	72	560	33	31	1.82	31	33
Pork	4,907	459	622	2,786	105	259	2.15	57	23
Sheep/goat	8,253	457	53	2,059	139	163	4.25	63	54
Beef	14,414	550	451	1,513	138	101	10.19	112	153

Adapted from [Mekonnen and Hoekstra \(2012\)](#).

IMPROVEMENTS OF WUE

Improvements of WUE at the Plant Level

Water use efficiency is by definition an additional unit of DM produced per additional unit of water used in the process. Instantaneous WUE can be easily calculated, but it is actually the linear regression from low to high amounts of water vs. DM production that will establish WUE. A very good overview of WUE was provided by [Kramer and Boyer \(1995\)](#) who provided data from C_3 (cool-season) and C_4 (warm-season) crops and showed that the slope is indeed steeper for C_4 plants (e.g., corn compared with alfalfa, which is a C_3 plant).

Discussing WUE in the context of LCA is crucial as upward of 90% of water moves through land plants for cooling purposes ([Kramer and Boyer, 1995](#)) and is not available for generating biomass. The adaptation mechanism of tropical grasses to water shortages and droughty conditions is the C_4 -photosynthetic pathway as this resulted in increased WUE. Modern improved forage grasses are either C_3 or C_4 and are used depending on location, adaptation, and economic goals. Although C_4 grasses are roughly twice as water-use-efficient as C_3 grasses ([Taylor et al., 1983](#)), there are still large amounts of water required to generate sufficient amounts of DM from C_4 grasses to support viable forage-based cattle operations. In addition, C_4 forage species, especially perennial ones, require overall warmer growing conditions for long-term survival than their C_3 counterparts.

Substantially enhancing WUE at the plant level would seem to require that the C_4 photosynthetic pathway is engineered into a C_3 plant. This, so far, seems not entirely feasible due to the complexity of photosynthesis and the number of regulatory genes ([Miyao, 2003](#)). However, there are several agronomic

tools at hand that can help improve WUE at the plant level. It should be remembered that WUE is the amount of DM or economic yield produced per unit of water. Total seasonal DM yields are a reflection of WUE for the usage of available soil water. Therefore, many of the possible improvements in WUE can be realized through ongoing intensification of agriculture, such as using improved forage varieties or optimizing fertilizer applications. Land plants mostly retrieve water from the soil; therefore, management of soil resources toward greater water availability is fundamental. This is especially important for the eastern United States where irrigation of forage crops and pastures is rare.

[Hatfield et al. \(2001\)](#) provided an excellent review of WUE responses to cropping practices. Although most of their examples were not forage-specific, data shown in their paper for various grain crops such as corn and sorghum pointed to the importance of optimizing crop management including fertilization and variety selection. Some examples in their paper suggested that WUE increased with increasing N fertilization, but this was also soil-specific. [Stout and Schnabel \(1997; cited by Hatfield et al., 2001\)](#) indicated that WUE for perennial ryegrass (*Lolium perenne* L.) ranged from 2.2 to 7.7 kg/ha⁻¹ mm⁻¹ as N applications increased from 0 to 126 kg/ha. [Hatfield et al. \(2001\)](#) also pointed out that WUE in poorly drained soils will be lower for this annual grass species, as denitrification likely reduced access to N despite fully available soil water. There are other potentially negative effects to be expected from excessive N fertilization of course. Only about half of applied N fertilizer will be incorporated into plant protein, so increasing N-use efficiency needs to go along with optimizing WUE for the most efficient forage production. Efficient N fertilization is especially challenging under rain-fed crop and pasturing conditions, where N-use efficiency greatly depends

on soil water availability that cannot be realistically controlled under nonirrigated conditions. Advantage may be taken of the lower N fertilizer needs of native warm season grasses such as big bluestem or switchgrass. Research on filter strips surrounding cropland showed that these strips could reduce annual nitrate losses up to 67% in a study conducted by Zhou et al. (2014) in central Iowa, so some negative impacts could be mitigated.

Research by Philipp et al. (2005, 2006, 2007) showed that increasing amounts of irrigation will reduce WUE and also alter parameters such as neutral detergent fiber, acid detergent fiber, and crude protein including some minerals. This implies consequences for managing forages, as the highest achievable WUE does not necessarily mean optimum forage nutritive value and therefore animal gain. Increased plant maturity correlates with decreased nutritive value and can be, within limits, managed through grazing or haying intervals that keep forages in the vegetative growth stage as much as possible.

Improvements of WUE at the Field Level

Water use efficiency at the field level largely depends on underlying structures including soil textures and topographic features across pastures such as slopes and a spatially changing hydrology. Because plants have to transpire very large amounts of water to generate DM, understanding basic water dynamics in a field setting is crucial for increasing forage production, improving forage stand persistence, drought resilience, and other factors that are related to WUE.

The amount of available soil water is difficult to control, but the placement of forage species and management depending on the site can be controlled at the field level. Scientists from the USDA-ARS Fayetteville and Booneville, AR, stations have initiated a soil mapping project in an agroforestry site located at the University of Arkansas—Division of Agriculture in Fayetteville with the purpose of spatially evaluating soil water content and nutrient concentrations. Initial mapping data showed (P. Owens, unpublished data) that soil depth correlated with water holding capacity and the grazing locations of GPS collar-equipped cattle based on forage preferences over the course of a 6-wk grazing event. Yellow nutsedge (*Cyperus rotundus*), which is not readily grazed by cattle, was prevalent in much wetter areas and cattle did not spend as much time there vs. other areas where orchardgrass (*Dactylis glomerata*) and a native grass

mix of mostly big bluestem (*Andropogon gerardii*) were dominant due to different soil textures (i.e., soil water contents).

While nutritional requirements of cattle can in theory be met through a range of cool- and warm-season forages, maximizing DM production and optimizing nutritive value evenly across an entire pasture are difficult. The concentration of macro- and micronutrients varies substantially across a site, and correcting deficiencies through precision agriculture techniques is possible, but economically likely not feasible for most grazing operations (Schellberg et al., 2008). In the agroforestry system mentioned above, the cooler microclimate and shaded alleyways may have a positive effect on WUE. The atmospheric evaporative demand will be lower which should result in less cooling requirements for plants being grown in the alleyways.

Improvements of WUE at the Landscape Level

Water use efficiency at the landscape level is a reflection of ecological, economical, and societal aspects. Although agriculture as a whole uses large amounts of fresh water resources, especially for field crops, grazing land differs from cropland substantially regarding the amount of ecosystem services provided. Based on a review by Silveira et al. (2010), naturalized (man-made) grasslands may not differ much from their natural, native counterparts in terms of environmental impacts. This is of importance especially for mitigating conflicts in urban–rural transition zones where competition for finite water resources is fierce. Grazing lands with the main purpose of animal output can successfully be managed for maintaining crucial ecosystem functions without loss of meat production. As very large amounts of water are being cycled through grasslands to maintain biomass production for grazing animals, water quality functions can be performed to filter runoff, remove excess nutrients with buffer strips, and supply adjacent biomes with subsurface flow. This will increase WUE at the landscape level, as the water use for plant growth is also linked to a host of services that originate from managing for a particular grassland ecosystem function. In an example from southern Florida, Bohlen et al. (2009) reported on a program that enables ranchers north of the Florida Everglades to retain water for maintenance of this large wetland area through direct payments for their services. The problems in the Everglades region are emblematic for many other regions in the United States and worldwide: fragmentation of wildlife habitat, movement of

nutrients, and subsequent water quality impairments of water bodies. With payments to ranchers, water management alternatives to flow-control structures could be established that retained water and established wetlands upstream of the Everglade area to buffer for adverse environmental effects resulting from past management practices.

A broader picture of potentially comprehensive grassland ecosystem services was provided by Hönigova et al. (2012) based on a review of grasslands located in the Czech Republic. Besides the livestock provision (i.e., producing meat) grasslands are capable of potentially adding income to farm families by monetizing additional ecosystem services, according to these authors. It is estimated that in “pastures and managed grasslands,” approximately \$1,000/ha per annum in value could be expected from water regulation. So far, such numbers are hypothetical, as those were based on the equivalent costs for cleaning the same amount of water at a conventional waste water treatment plant. Because both natural and naturalized grasslands cover large connected areas in the United States, these areas would also be supremely suited to filter nutrients, slow runoff, and recharge aquifers. Grasslands have been used to mitigate effluent and provide areas to apply manure slurry from concentrated feeding operations, and it is estimated that the outflow of nitrogen from grasslands is about 10 times lower than from arable land, according to Jankowska-Huflejt (2006).

SUMMARY AND CONCLUSIONS

Life cycle assessments are useful tools for tracking and analyzing the environmental impacts over the life span of a product, usually from “cradle-to-grave” or from “birth-to-farm gate” as is usually the case in livestock production. Of interest to producers and consumers are impacts of a defined functional unit to the environment, such as kg of CO₂-e per kg of beef produced. Water footprints are like LCA that is solely concerned with the impact of the amount of water utilized during the production, utilization, and disposal processes of a product or product group. The calculated quantities of green water needed to obtain meat from forage-based livestock production systems are large, but these quantities also support specific grassland ecosystem functions which would be diminished or disappear if pastureland would be converted to cropland for the sake of reducing the water footprint for a single food product. Therefore, any effort in reducing water footprints should be made within the context of changing land use, and resulting the ecological, economic, and social effects.

Regardless of the evolving interpretation of water footprints, opportunities exist to improve WUE at the plant, field, and landscape level in forage-based livestock systems. Selecting appropriate forage species and varieties, adjustment of agronomic practices, and strategic placement of forages based on soil parameters and landscape features can increase DM production and thereby increase WUE. In addition, grasslands, including naturalized grasslands on which most of cow-calf operations in the United States are located, provide a multitude of ecosystem services that are currently not sufficiently reflected in LCA and water footprint calculations.

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