

Water footprint of livestock: comparison of six geographically defined beef production systems

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Abstract

Purpose Water use in the livestock sector has featured in the debate about sustainable food systems. Most evidence has come from virtual water calculations which lack impact assessment and adequate consideration of the heterogeneity in livestock production. This study sought new evidence, using a recently developed life cycle impact assessment method for water use to assess six geographically defined beef cattle production systems in New South Wales, Australia, a major production region.

Methods The livestock production systems were diverse in farm practice (grass and feedlot finishing), product (yearling to heavy steers), environment (high-rainfall coastal to semi-arid inland) and local water stress. Life cycle inventories were developed from representative farm enterprise budgets. The farm water use inventories sought

to describe the impact of the production system on catchment water resources and included irrigation water use as well as the reduction in flows due to the operation of stock dams.

Results and discussion The normalised life cycle impact category results for water use, referred to as the water footprint, ranged from 3.3 to 221 L H₂Oe kg⁻¹ live weight at farm gate. Due to variation in local water stress, the impact category results were not correlated with the inventory results.

Conclusions The substantial variability in water footprint between systems indicates that generalisations about livestock and livestock products should be avoided. However, many low input, predominantly non-irrigated, pasture-based livestock production systems have little impact on freshwater resources from consumptive water use, and the livestock have a water footprint similar to many broad-acre cereals. Globally, the majority of beef cattle are raised in non-irrigated mixed farming and grazing systems. Therefore, the general assertion that meat production is a driver of water scarcity is not supported.

Keywords Agriculture · Environmental labelling · Livestock · Meat consumption · Water footprint · Water scarcity · Water stress · Water use

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1 Introduction

The development of methods to address water use is an important innovation occurring in life cycle assessment (LCA) (Berger and Finkbeiner 2010), currently supported by a project group working under the auspices of the United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry (UNEP–

SETAC) Life Cycle Initiative (Koehler 2008; Bayart et al. 2010). Water is a critical resource supporting human and ecosystem health, and water use is the major environmental burden in some product systems (Pfister et al. 2009).

The problem is not that there is an absolute scarcity of freshwater in the world, but rather that the pattern of freshwater consumption is greatly skewed toward highly stressed watersheds (Ridoutt and Pfister 2010b). The result is a long and growing list of major river systems where flows have become severely reduced and in some cases intermittent in the lower reaches (Falkenmark and Lannerstad 2005), as well as situations of serious groundwater depletion (Kerr 2010; Qui 2010) and freshwater quality degradation. The problem is of sufficient global concern that planetary environmental boundaries for freshwater use have been proposed (Rockström et al. 2009), analogous to the boundaries proposed for global greenhouse gas emissions, in order to avoid widespread irreversible environmental change and intolerable impacts on human well-being.

Agriculture is by far the largest consumer of freshwater globally, accounting for around 70% of withdrawals (UNESCO-WWAP 2009). As such, the agri-food sector is of particular relevance in understanding and addressing the challenges of global water stress. The situation of water use in agriculture is made even more acute by the increasing world population, concerns about global food security (FAO 2008) and forecasts indicating that most population growth will occur in regions already experiencing water stress (UNESCO-WWAP 2009). The potential for water scarcity to limit food production is obvious.

Reducing the pressure on freshwater resources from agriculture and food production is a critical challenge facing humanity. What is unclear is how to achieve this goal. Reducing the consumption of meat and other livestock products is a common recommendation (Pearce 1997; Steinfeld et al. 2006; Marlow et al. 2009; Nellemann et al. 2009; Mekonnen and Hoekstra 2010). For example, Liu et al. (2008) argue that the changing food-consumption patterns, toward greater consumption of meat, are the main cause of worsening water scarcity in China. However, as described by Ridoutt et al. (2011), the evidence base to support such generalisations is debated and based almost entirely on estimates of the virtual water content of meat products, which can be as high as 200,000 L kg⁻¹ by some accounts (Thomas et al. 1997). The problem with virtual water accounting is that it fails to describe the environmental relevance of water use in a product life cycle, which depends particularly on the type of water being used and the degree of local water stress (Ridoutt et al. 2009). Case study evidence has shown that the virtual water content

of a product is not correlated with the environmental impact of water use, assessed using an LCA-based impact assessment model (Ridoutt and Pfister 2010a; Ridoutt and Poulton 2010).

Our research concerns the application of a single indicator LCA-based water footprint calculation method to assess water consumption in six geographically defined beef cattle production systems in the Australian state of New South Wales (NSW), a major production region. Pollution aspects of water use were not considered. The research is novel in two respects. Firstly, we have taken a more comprehensive approach to modelling farm water-use than has previously been undertaken in LCA studies of grass-fed livestock. In many extensive cattle production systems the provision of drinking water is the major water-use activity. The approach taken to estimating drinking-water consumption and related evaporative losses is therefore influential in the overall water footprint calculation. Secondly, by assessing six systems, diverse in both farm practice and geography, we have sought insight into the typical range in water footprint for beef cattle production in NSW and an understanding of the major sources of variation. Assessment of variation is important because cattle production systems differ greatly. Our primary purpose is to provide strategic insights that will assist the livestock sector to minimise its burden on freshwater systems. We also aim to contribute to the debate about sustainable food systems and the role of livestock products.

2 Methods and data

2.1 System description

Beef cattle production occurs throughout most parts of Australia, in a wide range of environments and production systems, on almost 60,000 individual properties (ABS 2010). This study focuses on the second largest region of beef production, NSW (5.9 million head, ABS 2010), where cattle are predominantly raised in mixed (i.e. livestock and cropping) farming systems. As the goal of the study was to assess the typical range in water footprint and the major sources of variation, six geographically defined production systems were selected (Table 1) to cover a broad range of production method (pasture and feedlot finishing), product (yearling through to heavy steers), environment (high-rainfall coastal country to semi-arid inland country) and local water stress (as defined by the Water Stress Index, WSI, Pfister et al. 2009). Briefly, the WSI is based on the water use to availability ratio with modifications to account for monthly and annual variability of precipitation and corrections to account for watersheds

Table 1 Summary of the six geographically defined beef cattle production systems in New South Wales, Australia

Production system	Main product	Location(s)	Mean max temp (°C)	Mean min temp (°C)	Mean rainfall (mm yr ⁻¹)	WSI
Japanese ox—grass-fed steers	24–36-mth-old steers 340 kg DW ^a	Scone	24.1	11.0	644	0.032
EU cattle	24–30-mth-old steers 280–300 kg DW	Parkes	23.4	10.9	584	0.815
Inland weaners, grass fattened and feedlot finished	24-mth-old steers 585 kg LW	Walgett	26.9	12.5	477	0.021
		Gunnedah	26.0	10.9	619	0.021
		Quirindi	24.6	8.9	683	0.021
North coast weaners, grass fattened and feedlot finished	24-mth-old steers 585 kg LW	Casino	26.7	13.2	1096	0.012
		Glen Innes	19.4	7.3	849	0.021
		Rangers Valley	19.4	7.3	849	0.021
Yearling	12–15-mth old yearling 185–205 kg DW	Gundagai	22.3	8.5	713	0.815
Yearling	12–15-mth-old yearling 185–205 kg DW	Bathurst	19.8	6.8	635	0.021

WSI water stress index (Pfister et al. 2009)

^a DW: dressed weight or dressed carcass weight after removal of hide, head, feet, tail and internal organs

with strongly regulated flows. The WSI follows a logistic function and ranges from 0.01 (lowest water stress) to 1 (Pfister et al. 2009). In this study, the locations with the highest WSI (Parkes and Gundagai; Table 1) are both within the middle section of the Murray Darling Basin where it is well known that water use has compromised environmental flows (Roderick 2011). The functional unit was 1 kg live weight (LW) of beef cattle at the point of sale to the processor. The system boundary was from cradle to farm gate and included all of the direct farming inputs (including replacement heifers and bulls), but excluded capital items, such as machinery, buildings and other infrastructure, as well as items associated with farm overheads, such as the operation of a farm office and the provision of farm financing. For predominantly extensive farm production systems, these items are considered minor and practically they are difficult to ascertain and can vary from one enterprise to another for reasons that have little relationship to production.

The reporting period was 1 year based upon farm enterprise budgets for the most common beef cattle production systems in NSW published by the NSW government (NSW I&I 2010; Table 2) as a planning tool to assist farmers to evaluate business options. These are regarded as being realistic and achievable by most professional farmers given good management practices. Consistent with these enterprise budgets, the life cycle modelling was based on a nominal enterprise unit of 100 cows at the commencement of mating, with sufficient heifers retained for breeding to achieve a stable herd population on an annual basis. We acknowledge that this is a simplification, necessary for the sake of modelling, and that in practice, on any particular farm, herds may increase

or decrease or change in structure for a wide range of reasons. For each production system, the number of animals of each class was calculated on a daily basis, taking into account the number and timing of sales, mortality and culls as well as the age of cows at first calf described in the enterprise budgets. Mating was assumed to occur from December to January, with gestation of 284 days. Replacement yearling bulls were assumed to be purchased on October 1 and cull-for-age bulls disposed at the end of February. In relation to co-products, including heifer weaners and culls, an economic approach to allocation was used. Life cycle inventories for water consumption in the Australian agricultural sector are not yet sufficiently developed to enable a systems expansion approach to allocation.

2.2 Summary of water flows quantified

The life cycle inventory sought to quantify changes in freshwater availability through water consumption. This included flows from surface and groundwater into the farming system to irrigate pastures as well as crops used for supplementary feeding and in the feedlot (where relevant). Secondly, it included the reduction in flows from the farming land base to surface and groundwater as a result of the operation of farm dams for livestock watering. Here, the reference was the flow of precipitation to surface and groundwater in the absence of livestock and dams. Finally, the water use associated with the production of inputs to farming (fuels and fertilizers, etc) and transportation processes (fuel) were quantified using secondary data. The details of the life cycle inventory modelling follow.

Table 2 Characteristics of the six beef cattle production systems in NSW, Australia

Production system	JO-S	EU-P	IGF	NGF	Y-G	Y-B
Farming subsystem						
Pasture land use						
Unimproved pasture (ha yr ⁻¹)	400	0	372	254	0	0
Non-irrigated improved pasture (ha yr ⁻¹)	90	295	61	36	207	211
Irrigated improved pasture (ha yr ⁻¹)	2	0	1	0	4	0
Irrigation of pasture (ML ha ⁻¹ of irrigated pasture)	2.6	0	2.0	0	1.3	0
Livestock						
Cows at time of mating (head)	100	100	100	100	100	100
Age of cows at first calf (month)	24	24	24	36	24	24
Calves (head yr ⁻¹)	86	86	84	64	86	86
Replacement heifers (head yr ⁻¹)	20	20	21	18	20	20
Bulls (head 100 cows ⁻¹)	3	3	3	3	3	3
Replacement bulls (head yr ⁻¹)	0.75	0.75	0.75	0.6	0.75	0.75
Mortality and culls (head yr ⁻¹)	23	22	22	20	22	22
Animals sold to feedlot or market, excl culls (head yr ⁻¹)	63	64	62	44	64	64
Fodder crops (ha yr ⁻¹)	20	25	8	5	0	0
Supplementary feed						
Grain (t yr ⁻¹)	6.9	0	8.3	0	0	0
Hay (t yr ⁻¹)	4.0	0	4.8	0	0	0
Fuel for pasture maintenance (kJ yr ⁻¹)	1.5	4.3	0.9	0.8	3.7	3.3
Fertilizer for pasture maintenance (t yr ⁻¹)	4.5	13.2	2.9	2.3	11.5	10.2
Marketing costs ('000 AUD yr ⁻¹)	2.6	3.2	6.1	3.5	4.3	4.3
Veterinary medicines ('000 AUD yr ⁻¹)	1.7	1.4	1.6	2.1	1.2	1.2
Feedlot subsystem						
Initial live weight (kg head ⁻¹)	–	–	420	340	–	–
Final live weight (kg head ⁻¹)	–	–	585	585	–	–
Days in feedlot (days head ⁻¹)	–	–	100	130	–	–
Water use (L head ⁻¹ day ⁻¹)	–	–	41.4	46.6	–	–
Fuel use (MJ head ⁻¹ day ⁻¹)	–	–	3.0	3.5	–	–
Electricity (%)	–	–	25	25	–	–
Natural gas (%)	–	–	40	40	–	–
Diesel (%)	–	–	35	35	–	–
Feedlot ration (kg head ⁻¹ day ⁻¹)	–	–	11.0	12.6	–	–

The purpose of this table is to provide an overview of the various production systems. It is not a complete life cycle inventory. These data are representative of the general situation over several years.

JO-S Japanese ox grass-fed steers (Scone); *EU-P* EU cattle (Parkes); *IGF* inland weaners, grass fattened and feedlot finished (Walgett, Gunnedah, Quirindi); *NGF* north coast weaners, grass fattened and feedlot finished (Casino, Glen Innes, Rangers Valley); *Y-G* yearling (Gundagai); *Y-B* yearling (Bathurst)

2.3 Life cycle inventory

The production systems varied in complexity. The simplest system involved yearling cattle born and raised to marketable age and size in a single enterprise operation. The most complex systems involved weaner production, grass fattening and then feedlot finishing in three separate enterprise operations. Figure 1 provides an overview of such a system and the components included in the inventory modelling. Inputs to each farming subsystem,

consisting of replacement bulls, fertilizer and fuel for the maintenance of improved pasture, supplementary feeds, veterinary medicines and marketing services, were tabulated based on the farm enterprise budgets (NSW I&I 2010), adjusted to account for average rainfall in each geographical location using an economic model (Kelliher 2009). Fodder crops were assumed to be dual-purpose oats grazed during the winter period of lowest pasture production and later harvested and conserved for supplemental feeding in late summer, which is a common

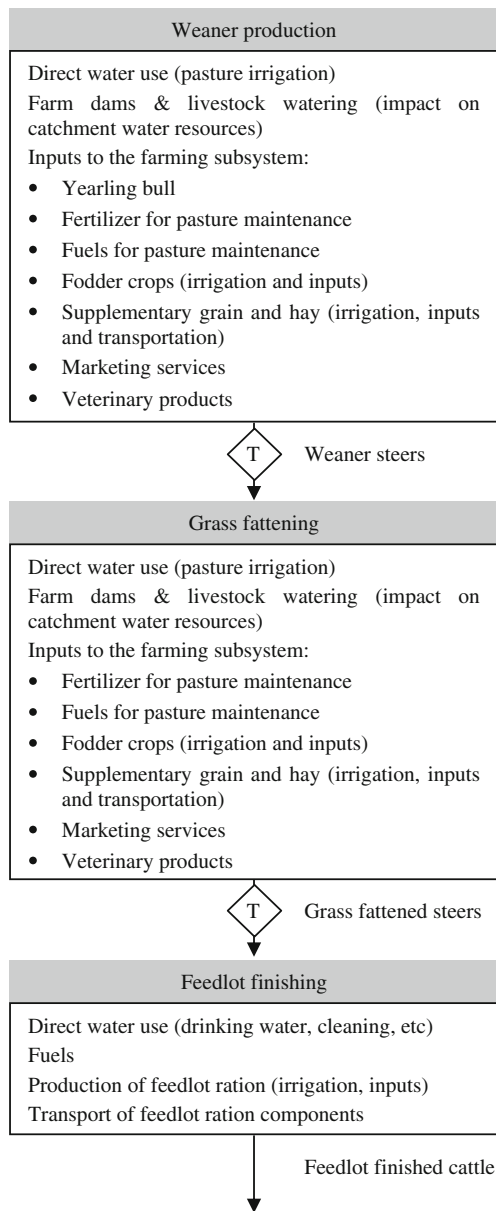


Fig. 1 Example of an Australian beef cattle production system showing the components included in the water footprint modelling. *T* livestock transport

practice in NSW. Creep feeding, a management practice allowing calves access to additional feed while they are still suckling, was assumed to consist of 60% locally grown grain (oats and lupins) supplemented with pasture hay (Hurst 2005).

Water use associated with the production of non-agricultural inputs (fuels, fertilizers, etc) generally makes a minor contribution to the water footprint of broad-acre agricultural products (Ridoutt and Poulton 2010), and values were obtained from the Australian Unit Process LCI. Due to the historical development of this database, water use is not always clearly defined. The use of data

describing water intake rather than water consumption would lead to a slight overestimate in the water inventory and water footprint in this study. Marketing services and veterinary products were modelled as other business services and pharmaceuticals using environmental input–output data (Foran et al. 2005). Irrigation water use for the production of pasture for grazing, pasture for hay, as well as other crops, was obtained from farm survey data collected by the Australian Bureau of Statistics (ABS 2008b, 2009), with adjustments made to account for the irrigation of pasture in the dairy sector (Khan et al. 2010). In the farming subsystem, water is also collected locally in farm dams and used to provide livestock drinking water. This represents a volumetric impact on catchment water resources to the extent that groundwater recharge and stream flows are reduced. As farmers do not account for this local water use, the quantities used were modelled, taking into account the farm herd structure and the numbers of each class of livestock, the monthly water budgets for each class of livestock in each location, and the evaporative losses from farm dams in each location.

Monthly water budgets for each class of livestock in each location were calculated using Eqs. 1–8 which are relevant to temperate breeds belonging to the *Bos taurus* group, and which are derived from data in CSIRO (2007). The total water intake requirement ($W_{\text{total intake}}$, litres per day) is a function of dry matter intake (DMI, kilograms per day), mean temperature (T , degree C; with a minimum value of 15) and milk production in the case of lactating cows ($\text{Milk}_{\text{prod}}$, litres per day), Eq. 1. For pregnant cows, the total water intake requirement was increased by 20%. Free water drunk (W_{drunk} , litres per day) is a function of the total water intake requirement and the water available in feed (W_{feed} , litres per day), Eq. 2. Water available in feed is a function of DMI, feed moisture content (MC_{feed} , %) and milk consumption in the case of calves ($\text{Milk}_{\text{cons}}$, litres per day), Eq. 3. Water in faeces (W_{faeces} , litres per day), which is assumed to be lost to evaporation, is a function of DMI, feed digestibility (D , %) and dry matter content of faeces ($\text{DM}_{\text{faeces}}$, %), Eq. 4. Water evaporative loss from animals ($W_{\text{evap loss}}$, litres per day) is a function of mean temperature and DMI, Eq. 5. Water derived from metabolism ($W_{\text{metabolism}}$, litres per day) is a function of DMI and digestibility, Eq. 6. Water in weight gain ($W_{\text{weight gain}}$, litres per day) is calculated, where relevant, in relation to weight gain (WG, kilograms per day) according to Eq. 7. Water in urine (W_{urine} , litres per day), assumed to be returned to the soil in the case of roaming animals, was calculated by difference, Eq. 8. Pasture moisture content, on a monthly basis, was obtained from GrassGro® (<http://www.grazplan.csiro.au>), and seasonal live weight, live weight gain and dry matter intake for each class of livestock were obtained from the Australian

Methodology for the Estimation of Greenhouse Gas Emissions and Sinks (NGGIC 2007).

$$W_{\text{total intake}} = \text{DMI} \times 1.445 \times \exp(0.055T) + \text{Milk}_{\text{prod}} \quad (1)$$

$$W_{\text{drunk}} = W_{\text{total intake}} - W_{\text{feed}} \quad (2)$$

$$W_{\text{feed}} = \frac{\text{DMI} \times \text{MC}_{\text{feed}}}{100 - \text{MC}_{\text{feed}}} + \text{Milk}_{\text{cons}} \quad (3)$$

$$W_{\text{faeces}} = \frac{\text{DMI} \times (100 - D)}{\text{DM}_{\text{faeces}}} \quad (4)$$

$$W_{\text{evap loss}} = C + (W_{\text{total intake}} - 3.3 \times \text{DMI});$$

$$C = 2.4 \text{ for calves, } 3.4 \text{ for cows and bulls} \quad (5)$$

$$W_{\text{metabolism}} = 0.6 \times \text{DMI} \times \frac{D}{100} \quad (6)$$

$$W_{\text{weight gain}} = 0.36\text{WG} \quad (7)$$

$$W_{\text{urine}} = W_{\text{feed}} + W_{\text{drunk}} + W_{\text{metabolism}} - W_{\text{faeces}} - W_{\text{evap loss}} - W_{\text{weight gain}} \quad (8)$$

It is estimated that 8,000 GL of water is potentially stored in more than 2 million farm dams across Australia (AWA 2010). The losses from evaporation are not known with certainty due to the difficulty in direct measurement of inflows and outflows and the complexity of modelling evaporation from the surface of small bodies of water (Craig 2006; Hipsey 2006). That said, the losses are

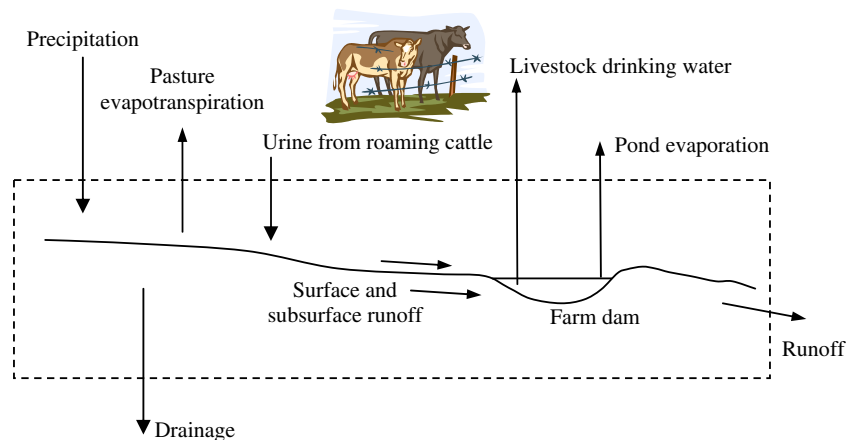
regarded as large, and efforts are underway in Australia to develop cost-effective farm dam evaporation mitigation technologies (Watts 2005; Baillie 2008). In this study, 40% of water in storage was assumed to be lost to evaporation at the location with the highest potential evaporation (ET_o). This figure corresponds with the upper estimate of water lost to evaporation from farm dams in Australia by experienced agricultural engineers (Baillie 2008). At other locations, the water in storage lost to evaporation was scaled downward based on the local ET_o, which has been found to correlate well with evaporation from small farm dams of about 50-m dimension or less (Craig 2006). To determine water in storage, a demand factor (i.e. the number of times a dam is emptied through extractions in 1 year) of 0.5 (Cetin et al. 2009) and a storage factor (i.e. the average volume in storage as a proportion of dam capacity) of 0.6 (Baillie 2008) were used.

These data were used to quantify the reduction in drainage and runoff as a result of the on-farm collection and use of precipitation. The generalized equation of Zhang et al. (2001), relating evapotranspiration (ET, millimeter) to precipitation (*P*, millimeter) for grassed catchments (Eq. 9), was used to determine the baseline situation in the absence of production (i.e. no dams and livestock). The difference between *P* and ET was assumed to contribute to either groundwater or runoff. The model was then re-run, taking into account the collection of runoff in farm dams, losses via evaporation from farm dams, water consumed by livestock and the return to pasture of water in urine from roaming animals (Fig. 2). The difference in drainage and runoff between the situations with and without dams and livestock was attributed to the production system.

$$\text{ET} = \left(\frac{1 + 0.5 \frac{1100}{P}}{1 + 0.5 \frac{1100}{P} + \frac{P}{1100}} \right) P \quad (9)$$

In the feedlot subsystem, water and energy use was calculated using data reported in a benchmarking study of Australian beef cattle feedlots (Davis and Wiedemann

Fig. 2 System boundary for modelling the change in drainage and stream flow arising from the collection of water in stock dams and use for livestock watering



2009). The composition of the feedlot ration was based on detailed, multi-year records provided confidentially by a large feedlot operator. Consumptive water use associated with the production of each feed component was calculated using national statistics (ABS 2008a, 2008b) and various CSIRO data sources (e.g. Ridoutt and Poulton 2010). The EcoInvent v2 database (<http://www.ecoinvent.org>) was the source of water use information for mineral supplements (<0.01% by mass). The feedlot operator also provided data on the transportation distances of the feed components which were used to calculate fuel use in transporting commodities to the feedlot.

This approach to creating an inventory of consumptive freshwater use is consistent with the principle described by Ridoutt and Pfister (2010a) of taking into account the way the production system limits the availability of freshwater for the environment and other human uses. As such, in the farming subsystem the emphasis was on characterising irrigation inputs and changes in catchment water balances due to farm dams and livestock watering. The evapotranspiration from pasture consumed by the livestock was excluded. As argued elsewhere (Ridoutt and Pfister 2010a), the consumption of so-called green water (local soil moisture derived from natural rainfall over agricultural lands) does not contribute to regional freshwater scarcity. Until it becomes part of the surface and groundwater system, green water does not contribute to environmental flows which are needed for the health of freshwater ecosystems, nor is it accessible for other human uses beyond the immediate property. Green water is only accessible through the direct occupation of land. The exception to this principle is where land transformation causes a change in the proportion of precipitation that becomes stream flow and deep drainage. Although not relevant to this study, the conversion of pasture to industrial forest could be one such example (Gilfedder et al. 2010).

2.4 Life cycle impact assessment

A single indicator water footprint was calculated following the method of Ridoutt and Pfister (2010a), using local

characterization factors for freshwater consumption taken from the Water Stress Index (WSI) of Pfister et al. (2009). The average Australian WSI (0.402) was used in relation to farm inputs where the location of production was uncertain. In performing the impact assessment, each instance of consumptive water use was multiplied by the relevant WSI and then summed across the product life cycle (from cradle to farm gate). The result was subsequently divided by the global average WSI (0.602) and expressed in the units H₂O equivalents (H₂Oe; Ridoutt and Pfister 2010a). The resulting water footprint results can be related to an equivalent volume of freshwater consumption at the global average WSI.

3 Results

For the six geographically defined beef cattle production systems in NSW, the consumptive water use ranged from 24.7 to 234 L kg⁻¹ LW, and the water footprint ranged from 3.3 to 221 L H₂Oe kg⁻¹ LW (Table 3). Here, water use refers to the consumption of freshwater from ground and surface water resources (i.e. there is no verifiable return to the local source of origin), as well as the volumetric impact on ground and surface water resources arising from the local storage and use of water in stock dams. These water footprint results, expressed in the units H₂Oe, can be interpreted as follows: Each kilogram of live weight of yearling cattle produced in Bathurst, NSW, exerts an equivalent pressure on freshwater resources as the direct consumption of 3.3 L of water (at the global average WSI). It can be seen in these results that the water footprint sometimes exceeds the water use inventory result and at other times is less, depending on the local water stress in the particular locations where water is consumed in each production system. The water footprint result will exceed the inventory result when water is used in regions where the local WSI exceeds the global average WSI and, conversely, will be lower when water is used in regions where the local WSI is less than the global average.

Table 3 Consumptive water use (L kg⁻¹ LW) and water footprint (L H₂Oe kg⁻¹ LW) for beef cattle at farm gate

Production system (location)	Water use	Water footprint
Japanese ox—grass-fed steers (Scone)	234	14.4
EU cattle (Parkes)	53.5	68.3
Inland weaners/ grass fattened/feedlot finished (Walgett, Gunnedah, Quirindi)	160	9.1
North coast weaners/grass fattened/feedlot finished (Casino, Glen Innes, Rangers Valley)	139	7.7
Yearling (Gundagai)	167	221
Yearling (Bathurst)	24.7	3.3

Water use is defined in the text

To avoid possible misunderstanding, it is important to note that these water footprint results relate to a specific beef cattle production system in a specific location. For example, the results for Japanese ox grass-fed steers relate only to a nominal Japanese ox production system located near Scone, NSW. The results cannot be used to describe Japanese ox grass-fed steers more generally in NSW or Australia. Also, the results may not accurately describe any specific enterprise producing Japanese ox grass-fed steers located near Scone if the specific production system differs significantly from the nominal enterprise described in the NSW beef cattle enterprise budgets. That said, these enterprise budgets are regarded as being realistic and broadly representative (NSW I&I 2010). In the same way, the results are not necessarily descriptive of specific feedlot operations located in Quirindi or Rangers Valley. Rather, they relate to average feedlots nominally located in these locations. The specific location of production is a critically important factor in water footprinting due to the regional variation in water stress (Pfister et al. 2009).

The major components contributing to the life cycle (cradle to farm gate) consumptive water use and water footprint varied substantially between production systems (Fig. 3). For the production system with the highest water footprint (yearlings, Gundagai), it was the irrigation of pasture that made overwhelmingly the largest contribution to both the consumptive water use and water footprint. In other systems the largest contribution to the water footprint came from stock dams and livestock watering (EU Cattle, Parkes), feedlot finishing (production

systems beginning with inland weaners and north coast weaners) and farm inputs (yearlings, Bathurst). It is therefore difficult to make generalisations about the industry, except that production systems involving irrigation in high WSI locations will most likely have the highest results. In non-irrigated systems, evaporation from stock dams and livestock drinking water can contribute substantially to consumptive water use; however, the relevance of this water use to the water footprint depends on the local WSI. For EU cattle from Parkes, a high-WSI location (see Table 1), stock dams and livestock watering represented 90% of consumptive water use and 95% of the water footprint. This contrasts with yearling production in Bathurst (a low WSI-location), where stock dams and livestock watering also represented a high proportion of consumptive water use (84%) but only 22% of the water footprint. Only when the water footprint was very small did farm inputs (fertilizer, fuels, etc) make a major proportional contribution (e.g. yearling, Bathurst, where fertilizers were the major contributor to the water footprint). In some cases the component contributing most to the consumptive water use was not the component contributing most to the water footprint (Contrast Fig. 3a, b). This demonstrates the importance of water use impact assessment in LCA and further supports the finding that water use inventory and water use impact assessment results are not necessarily correlated (Ridoutt and Pfister 2010a; Ridoutt and Poulton 2010). Hence, the utmost importance of including impact assessment in any streamlined sustainability metric which aims to communicate the potential environmental impacts of water use.

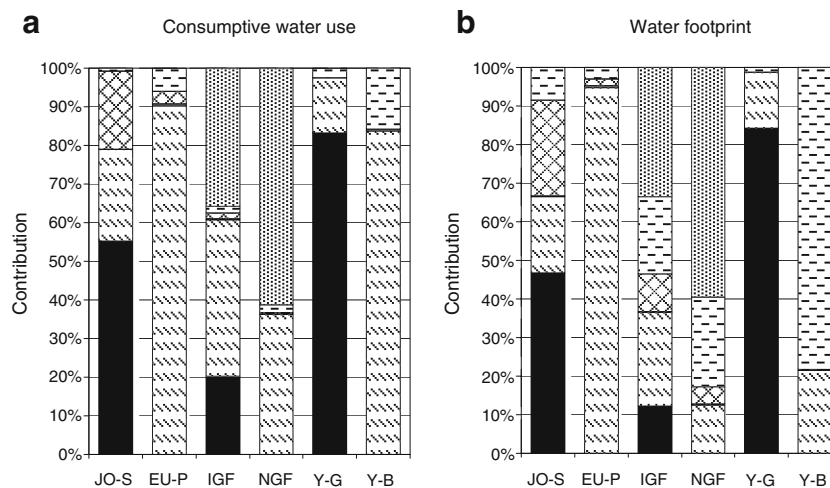


Fig. 3 Contribution to the life cycle (cradle to farm gate) consumptive water use (a) and water footprint (b) of six geographically defined beef cattle production systems in NSW, Australia. *JO-S* Japanese ox grass-fed steers (Scone); *EU-P* EU cattle (Parkes); *IGF* inland weaners, grass fattened and feedlot finished (Walgett, Gunnedah, Quirindi);

NGF north coast weaners, grass fattened and feedlot finished (Casino, Glen Innes, Rangers Valley); *Y-G* yearling (Gundagai); *Y-B* yearling (Bathurst). ■ Irrigation of pasture; ▨ Stock dams and livestock watering; ▩ Replacement bull; ▤ Supplementary feed; ▧ Other farm inputs; ▦ Feedlot finishing; ▧ Livestock transport

4 Discussion

Published estimates of the water required to raise beef cattle and to produce beef products vary enormously, from as little as 27 L kg⁻¹ Hot Standard Carcase Weight after processing (less than 15 L kg⁻¹ LW) to as much as 200,000 L kg⁻¹ beef (approximately 85,000 L kg⁻¹ LW) (Beckett and Oltjen 1993; Pimental et al. 1997; Thomas 1997; Berthelemy 2000; Chapagain and Hoekstra 2003; Pimental et al. 2004; Costa 2007; Hoekstra and Chapagain 2007; Deutsch et al. 2010; Peters et al. 2010). The variation arises largely from the use of different water accounting methods. The lowest reported water use estimates are from studies which have not considered all forms of consumptive water use. For example, Peters et al. (2010) used statistical records of extracted water, which omit the water use associated with farm dams. As such, in some cases their estimates of water use fall considerably below the basic drinking water requirements of cattle (Wiedemann and McGahan 2010). In many grass-fed production systems, the evaporation and use of water collected locally in stock dams is a large proportion of the total consumptive water use (see Fig. 3a).

The highest reported water use estimates are from studies including the evapotranspiration from pastures and rangeland consumed by the livestock (Pimental et al. 1997). The difficulty with this approach is that evapotranspiration from grasslands will occur even in the absence of production. We think that the most appropriate approach to creating an inventory of consumptive water use in grass-fed livestock production systems is to account for the change in catchment water resources. This requires assessment of the elementary flows of water from surface and groundwater resources across the system boundary into the farming system, as well as assessment of the reduction in flows from the land base across the system boundary to surface and groundwater due to farm dams and livestock. Taking this approach, and using Eqs. 1 to 9, water use was found to range from 24.7 to 234 L kg⁻¹ LW for the six beef cattle production systems in NSW, Australia.

A focus on the highest water use values has led some to conclude that meat production and consumption is a major threat to global freshwater availability (Pearce 1997; Steinfeld et al. 2006; Marlow et al. 2009; Nellemann et al. 2009; Mekonnen and Hoekstra 2010). However, as described previously, water use estimates for livestock based on the evapotranspiration from crops, pastures and rangelands do not reflect the likely change in catchment water resources. In addition, a water use inventory, without subsequent impact assessment, does not describe the environmental relevance of water used. A problem with the public communication of water use inventory results and virtual water estimates for livestock and meat is that

they may potentially be interpreted by a non-technical audience as an indicator of environmental sustainability. However, as shown in Table 3, the life cycle impact category result for water use (referred herein as the water footprint) was not correlated with the water use inventory result.

For the six beef cattle production systems in NSW, the water footprint ranged from 3.3 to 221 L H₂Oe kg⁻¹ LW. These results may not cover every extreme; however, they are an indication of the likely range of water footprint for beef cattle production in NSW. This range is also likely to be representative of other low input, mainly non-irrigated, predominantly pasture-based systems elsewhere in the world since the six production systems in NSW included both very high and very low WSI locations. According to de Haan et al. (2010), more than two-thirds of the world's cattle and buffaloes are raised in rain-fed mixed and grazing production systems.

Beef cattle production systems differ in farm practice and geography. Therefore, it can be misleading to report industry averages. As demonstrated in this research, some beef cattle production systems have very little potential to contribute to freshwater scarcity (<10 L H₂Oe kg⁻¹ LW, Table 3), and many have water footprints that fall within the same range as cereals. Whereas the water footprint of beef cattle at farm gate was found to range from 3.3 to 221 L H₂Oe kg⁻¹ LW, in a separate study, using the same impact assessment method, the water footprints of wheat, barley and oats grown in NSW were found to range from 0.9 to 152 L H₂Oe kg⁻¹ at farm gate (Ridoutt and Poulton 2010). This is not to exclude the possibility of higher water footprints where production systems rely to a greater extent on irrigation, especially in high water stress environments. However, these results evoke caution in making simplistic comparisons between the water footprints of meat-containing and vegetarian diets; to be insightful, such comparisons should take into account variability in farm production systems and geography, as well as the resource use and conversion efficiency in transforming farm produce into consumer food products. What we seek is constructive use of LCA-based water footprinting to inform and motivate producers and consumers alike to reduce pressure on freshwater systems from the agri-food sector.

5 Conclusions

Water use in the livestock sector has featured as an important part of the debate about the role of meat and other livestock products in a sustainable global food system. There is an important opportunity for LCA to inform this debate through the application of impact assessment models for water use. In this study, concerning

six geographically defined beef cattle production systems in NSW, Australia, the normalised life cycle impact category results for water use, referred to as the water footprint, ranged from 3.3 to 221 L H₂Oe kg⁻¹ LW. These results, for a single impact category, are not an indicator of overall environmental impact. However, they do indicate that many low input, predominantly non-irrigated, pasture-based live-stock production systems have little impact on freshwater resources from consumptive water use. In addition, the range in water footprint for these beef cattle production systems was not dissimilar to major cereal products cultivated in the same region of Australia. We conclude that generalisations about the water footprint of livestock products should be avoided. Livestock production systems are not all alike, and the local water stress where operations occur is an important factor. It is the variation in water footprint between production systems that needs to be explored and used to inform more sustainable forms of agri-food production and consumption.

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