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Water footprint of livestock

Impact assessment of beef production systems in NSW

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Abstract

For the agriculture and food sectors, environmental impacts from greenhouse gas (GHG) emissions, water use and land use are of particular concern to stakeholders and are important considerations in any industry strategy relating to environmentally responsible production. Tradeoffs between these impacts are also common and therefore integrated assessment is desirable. Life cycle assessment (LCA) was used to calculate the carbon and water footprints of beef cattle produced in six geographically-defined systems in New South Wales which were selected to be 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. An inventory of land use was also compiled. The carbon footprints ranged from 10.1 to 12.7 kg CO_2e/kg live weight (LW). The water footprints ranged from 3.3 to 221 L H_2Oe/kg LW, and were highest where irrigation occurred in high water stress locations. The large range in water footprint indicates that generalisations about the industry should be avoided. When the environmental impacts from GHG emissions and water use were aggregated, impacts from GHG emissions represented 94 to 99% of the combined scores, indicating that for these beef cattle production systems GHG emissions reduction is the higher priority.

Executive summary

This study provides new strategic insight into the environmental impacts of beef cattle production in southern Australia.

Firstly, for beef cattle raised in a diverse selection of case study production systems in New South Wales, water footprints were calculated using a life cycle assessment (LCA)-based approach, which takes into account the environmental relevance of the water being used. This approach contrasts markedly with volumetric approaches based on the concept of virtual or embedded water.

Secondly, environmental impacts associated with greenhouse gas (GHG) emissions and water-use were aggregated to enable their relative importance to be quantitatively compared.

Thirdly, for each case study production system, an inventory of land use was compiled. This will enable an integrated assessment of GHG emissions, water and land use when LCA impact assessment models for land use become sufficiently developed.

Case study production systems

Six geographically-defined beef cattle production systems were compared which 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 (Table 1). As such, the results are intended to be broadly indicative of the likely range of beef cattle produced in NSW. Geographical definition of the production systems was necessary because the water footprint calculations took into account the local water stress where operations occurred.

Table 1. Summary of the six geographically-defined beef cattle production systems.

Production system	Main product	Location(s)	WSI[a]
Japanese ox – grass-fed steers	24-36 month old steers 340 kg dressed weight	Scone	0.032
EU cattle	24-30 month old steers 280-300 kg dressed weight	Parkes	0.815
Inland weaners, grass fattened, and feedlot finished	24 month old steers 585 kg live weight	Walgett Gunnedah Quirindi	0.021 0.021 0.021
North coast weaners, grass fattened, and feedlot finished	24 month old steers 585 kg live weight	Casino Glen Innes Rangers valley	0.021 0.021 0.021
Yearling	12-15 month old yearling 185-205 kg dressed weight	Gundagai	0.815
Yearling	12-15 month old yearling 185-205 kg dressed weight	Bathurst	0.021

[a] WSI, Water Stress Index (Pfister et al., 2009, Environmental Science & Technology 43:4098-4104)

Water footprint results

Consumptive water use ranged from 24.7 to 234 L/kg live weight (LW) and the water footprint ranged from 3.3 to 221 L H_2Oe/kg LW at the point of marketing (Table 2). For explanation, a product with a water footprint of 1 L H_2Oe exerts equivalent pressure on freshwater systems (from water use in its production life cycle) as the direct consumption of 1 L H_2O at the global average water stress index (WSI). Due to variation in local water stress, the water footprint and water use results were not correlated.

The large range in water footprint indicates that generalisations about the industry should be avoided. That said, many low input, predominantly non-irrigated, pasture-based systems have little impact on freshwater resources from consumptive water use and the livestock have a water footprint similar to many broad acre cereals. The general assertion, that cattle production is a driver of water scarcity, is not supported.

Table 2. Water footprint (WF, L H_2Oe/kg LW), carbon footprint (CF, kg CO_2e/kg LW), and fraction of combined score related to GHG emissions.

Production system	WF	CF	GHG fraction
Jap-ox (Scone)	14.4	10.2	0.97
EU cattle (Parkes)	68.3	10.8	0.98
Inland weaners/grass fattened/feedlot finished (Walgett, Gunnedah, Quirindi)	9.1	10.1	0.94
North coast weaners/grass fattened/feedlot finished (Casino, Glen Innes, Rangers Valley)	7.7	12.7	0.97
Yearling (Gundagai)	221	10.4	0.95
Yearling (Bathurst)	3.3	10.6	0.99

Comparing carbon and water footprints

The carbon footprint ranged from 10.1 to 12.7 kg CO_2e/kg LW (Table 2), which is within the typical range for beef cattle raised on pasture. When the environmental impacts from GHG emissions and water use were aggregated, impacts from GHG emissions represented 94 to 99% of the combined scores (Table 2), indicating that for these beef cattle production systems GHG emissions reduction is the higher priority.

Industry benefits

- At present, there are various claims made in the popular and scientific media about the water footprint of red meat, with some published estimates based on the virtual water content approach as high as 200,000 L/kg beef. These estimates, which do not consider the environmental relevance of the water used, have the potential to be misleading and to undermine the reputation of Australian beef. This report presents new evidence, based on LCA and consistent with the emerging international water footprint standard (ISO 14046), demonstrating that many Australian beef cattle production systems (as represented by the 6 diverse case studies) have little impact on freshwater systems from consumptive water use.
- In terms of prioritising future investment in environmental improvement, this research has demonstrated that, for beef production systems represented by the case studies, GHG emissions reduction is a higher priority than water footprint reduction.
- A method has also been demonstrated for assessing the tradeoffs between GHG emissions and water use.

Recommendations for future action

- This research, based on 6 case study systems, should be extended to enable a full national assessment to be completed. This will determine whether the conclusions reached in this study apply nationally and underpin national level reporting and communication activities.
- MLA should support the development of an international standard for water footprint and its adoption by the livestock sector internationally
- MLA should support the development of a balanced, multi-indicator approach to environmental assessment which includes carbon, water and land use footprints.

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1 Background

For agricultural products, the major environmental pressure points of international concern relate to greenhouse (GHG) emissions, water use and land use.

For the environmental impacts of GHG emissions, well established assessment protocols exist, based on life cycle assessment (LCA). The results are commonly referred to as a carbon footprint, expressed in the units CO_2e (equivalent).

Only recently have LCA-based methods begun to be developed to enable the environmental impacts of water use to be assessed for products (Berger and Finkbeiner, 2010). The results, which can be reported as a water footprint in the units H_2Oe (Ridoutt and Pfister, 2010), are fundamentally different from results obtained from simple calculations of water use, product virtual water content[1] and embedded water, which do not consider the environmental relevance of the water used. Due to the local and regional nature of water stress, metrics such as water use, virtual water and embedded water are not a reliable indicator of the environmental impact of a product. Case study evidence has shown that it is possible for a product with a small virtual water content to have a higher environmental impact from life cycle water use than a product with a much larger virtual water content (Ridoutt, 2011).

This study represents the first attempt to apply LCA-based water footprinting to livestock products arising from the beef cattle sector and therefore provides a new baseline for understanding and reporting water use impacts in this industry.

Assessing the impacts of land use in LCA is an active area of method development. Nevertheless, as a first step toward the integrated assessment of carbon, water and land-use footprints, an inventory of land use is compiled for the case study beef production systems assessed in this project.

Tradeoffs between GHG emissions, water use and land use are common in the agricultural sector. This is why integrated assessment is desirable and should be possible in the near future using LCA modelling. In this project we progress in this direction with an integrated assessment of carbon and water footprints. In so doing, the relative importance of the carbon and water footprints are compared.

The Australian red meat industry operates in a national and international context where environmental sustainability is of ever increasing importance. The main purpose of this project is to provide science-based evidence to inform the debate about sustainable food production and to inform wise decision making in the beef cattle sector.

2 Project objectives

The five project objectives were:

1. Calculate the water footprints of selected beef production systems (6 systems) in New South Wales and/or Queensland from cradle to farm gate. Here, the water footprint refers to an assessment of the impact of consumptive freshwater use.
2. Quantify the variation in water footprint between the selected beef production systems.
3. Quantitatively compare the water footprint of each system with the carbon footprint, which will also be calculated.

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[1] Virtual water (also called embedded water) refers to the total volume of freshwater used to produce a product or service, including water consumed in production and not physically present in the product.

4. Assess the major factors contributing to the water footprint and the potential for impact reduction.
5. Create an inventory of land use required for each beef production system. This will be an input to the development of a new LCA indicator (being developed in another project) which will assess the impact of land use on food production capability.

3 Methodology

3.1 System description

This study is based on six geographically-defined beef cattle production systems in NSW (Table 3). As the goal of the study was to assess the typical range in water footprint and the major sources of variation, the case studies were selected to cover a broad range of farm practice (grass and feedlot finishing), product (yearling to heavy steers), environment (high-rainfall coastal to semi-arid inland) and local water stress (as defined by the Water Stress Index, WSI, Pfister et al., 2009). The focus was NSW because it is a major region of beef cattle production (5.9 million head; ABS, 2010) and because of the availability of beef cattle farm enterprise budgets for a range of production systems published by the NSW government (NSW I&I, 2010; Appendix 1). These enterprise budgets exist as a planning tool to assist farmers to evaluate business options and, as such, they are considered broadly representative of the practices of professional farmers exercising good management practice.

Table 3. Summary of the six geographically-defined beef cattle production systems.

Production system	Main product	Location(s)	WSI[a]
Japanese ox – grass-fed steers	24-36 month old steers 340 kg dressed weight	Scone	0.032
EU cattle	24-30 month old steers 280-300 kg dressed weight	Parkes	0.815
Inland weaners, grass fattened, and feedlot finished	24 month old steers 585 kg live weight	Walgett Gunnedah Quirindi	0.021 0.021 0.021
North coast weaners, grass fattened, and feedlot finished	24 month old steers 585 kg live weight	Casino Glen Innes Rangers valley	0.021 0.021 0.021
Yearling	12-15 month old yearling 185-205 kg dressed weight	Gundagai	0.815
Yearling	12-15 month old yearling 185-205 kg dressed weight	Bathurst	0.021

[a] WSI, Water Stress Index (Pfister et al., 2009)

Consistent with the NSW beef cattle enterprise budgets, the modelling was based on a nominal enterprise unit of 100 cows at the commencement of joining, with sufficient heifers retained for breeding to achieve a stable herd population on an annual basis. We acknowledge that this is a necessary simplification 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. Joining 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 CFA bulls disposed at the end of February.

The basis for analysis, known as the functional unit in LCA, was one kg live weight (LW) of beef cattle destined for slaughter. This functional unit was chosen to enable comparison of livestock of varying age and size. The system boundary was therefore from cradle to farm gate and included all of the main direct farming inputs, but excluded capital items, such as machinery, buildings and other infrastructure, as well as items associated with farm overheads (e.g. operation of a farm office, farm financing). Inputs to the farming subsystem (Table 4), consisting of replacement bulls, fertilizer and fuel for the maintenance of improved pasture, fodder crops, supplementary feeds, veterinary medicines, and marketing services, were tabulated based on the NSW enterprise budgets (NSW I&I, 2010) and the RMCG Revised Economic Model (Kelliher, 2009), with adjustment to account for average rainfall in each geographic location. 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. Creep feeding was assumed to consist of 60% locally grown grain (oats and lupins) supplemented with pasture hay. In the feedlot subsystem (Table 5), water and energy use were calculated from data in the reports arising from MLA project B.FLT.0350. The composition of the feedlot ration was based on detailed, multi-year records provided confidentially by a large feedlot-operator. 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 using data on fuel usage reported in MLA project B.FLT.0350. The same fuel usage data source was also used in relation to the transportation of livestock.

In relation to co-products, including heifer weaners and culls, an economic approach to allocation was used.

Table 4. Characteristics of the farming subsystems of the 6 beef cattle production systems. 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)

Production system	JO-S	EU-P	IGF	NGF	Y-G	Y-B
Pasture land use (ha/yr)						
> Unimproved	400	0	372	254	0	0
> Non-irrigated improved	90	295	61	36	207	211
> Irrigated improved	2	0	1	0	4	0
Irrigation rate (ML/ha of irrigated pasture)	2.6	0	2.0	0	1.3	0
Livestock						
> Cows at time of joining (head)	100	100	100	100	100	100
> Age of cows at first calf (month)	24	24	24	36	24	24
> Calves (head/yr)	86	86	84	64	86	86
> Replacement heifers (head/yr)	20	20	21	18	20	20
> Bulls (head/100 cows)	3	3	3	3	3	3
> Replacement bulls (head/yr)	0.75	0.75	0.75	0.6	0.75	0.75
> Mortality & culls (head/yr)	23	22	22	20	22	22
> Prime cattle to feedlot/market (head/yr)	63	64	62	44	64	64
Fodder crops (ha/yr)	20	25	8	5	0	0
Supplementary grain (t/yr)	6.9	0	8.3	0	0	0
Supplementary hay (t/yr)	4.0	0	4.8	0	0	0
Fuel for pasture maintenance[1] (kl/yr)	1.5	4.3	0.9	0.8	3.7	3.3
Fertilizer for pasture[2] (t/yr)	4.5	13.2	2.9	2.3	11.5	10.2
Marketing costs[3] ('000 AUD/yr)	2.6	3.2	6.1	3.5	4.3	4.3
Veterinary medicines[4] ('000 AUD/yr)	1.7	1.4	1.6	2.1	1.2	1.2

[1] Fuel modelled as diesel
[2] Fertilizer modelled as DAP
[3] Marketing costs modelled as “Other business services” (Foran et al., 2005)
[4] Veterinary medicines modelled as “Pharmaceuticals” (Foran et al., 2005)

Table 5. Characteristics of the feedlot subsystems. 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)

Production system	IGF	NGF
Initial live weight (kg/head)	420	340
Final live weight (kg/head)	585	585
Days in feedlot (days/head)	100	130
Water use (L/head/day)	41.4	46.6
Fuel use (MJ/head/day)	3.0	3.5
> Electricity (%)	25	25
> Natural gas (%)	40	40
> Diesel (%)	35	35
Feedlot ration (kg/head/day)	11.0	12.6

3.2 Water footprint modelling

Water footprint modelling followed the process LCA-based water footprint calculation method of Ridoutt and Pfister (2010).

In the inventory phase, this led to an assessment of the way the production system limited the availability of freshwater resources (in surface and groundwater, but not soil moisture in the land resources that form part of the production system). The reasons for this have been well documented in the science literature and will not be elaborated again here (Ridoutt and Pfister 2010, Ridoutt 2011). As such, the emphasis was on characterising:

- Irrigation inputs (to pastures, fodder crops and in relation to the production of supplementary grain and hay and feedlot ration components),
- Changes in catchment water balances due to the operation of farm dams,
- Water use in the manufacturing of non-agricultural inputs (fuels, fertilizers, etc) and provision of farm services

Figure 1 provides an overview of a beef cattle supply chain and the components included in the modelling.

3.2.1 Irrigation

Irrigation water use for the production of pasture for grazing, pasture for hay, as well as other crops, was estimated from ABS statistics (predominantly 2005/06) and other CSIRO data, including data relating to the irrigation of pasture in the dairy sector (Khan et al., 2010). See Appendix 2.

3.2.2 Stock dams and livestock

In relation to water 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[2]:

- Average monthly pasture growth rates and digestibility which were used to calculate the moisture content of feed in each location (Appendix 3).

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[2] A complete set of equations can be found in Ridoutt et al. (2011).

- Seasonal live weights, live weight gains and dry matter intake for each class of livestock (Appendix 4)
- Monthly water budgets for each class of livestock (Appendix 5), taking into account:
    - Water available in feed (a function of dry matter intake, feed moisture content and milk consumption)
    - Total water requirement (a function of dry matter intake, mean temperature and milk production)
    - Free water drunk (a function of total water requirement and water available in feed)
    - Water in faeces (assumed to be lost to evaporation) (a function of dry matter intake, digestibility and dry matter content of faeces)
    - Water evaporative loss from animals (a function of mean temperature and dry matter intake)
    - Water in urine from roaming animals (assumed to be returned to the soil) (a function of water available in feed, free water drunk, metabolic water, water in faeces, water evaporative loss from animals, and water in weight gain)
- Farm herd structure and numbers of each class of livestock (Appendix 6).
- Evaporative losses from farm dams, taking into account a demand factor of 0.5 (Cetin et al., 2009) for stock dams, a storage factor of 0.6 (Baillie, 2008), local potential evaporation, and estimates of farm dam evaporative losses published by the National Centre for Engineering in Agriculture (Baillie, 2008). See Appendix 7.

These data were used to quantify the reduction in drainage and stream flow as a result of the on-farm collection and use of precipitation (Appendix 8). The generalized equation of Zhang et al. (2001), relating evapotranspiration (ET) to precipitation (P) for grassed catchments (Eq.1), was used to determine the baseline situation in the absence of production. The difference between P and ET was assumed to contribute to either groundwater or stream flow. 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 in the case of roaming animals.

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

3.2.3 Farm inputs

Values for consumptive water use associated with the production of non-agricultural inputs (fuels, fertilizers, etc) were obtained from the Australian Unit Process Life Cycle Inventory Database(Grant, 2010), the EcoInvent v2 database (http://www.ecoinvent.org), Australian environmental input-output data (Foran et al., 2005) and various CSIRO internal data sources.

3.2.4 Water footprint calculation

For impact assessment, local characterization factors for freshwater consumption were taken from the Water Stress Index (WSI) of Pfister et al. (2009). The average Australian WSI was used in relation to farm inputs where the location of production was uncertain. To calculate the water footprint, 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 water footprint was subsequently normalized by dividing by the global average WSI and expressed in the units H_2O equivalents (H_2Oe; Ridoutt and Pfister 2010).

3.3 Carbon footprint modelling

Carbon footprint modeling followed the approach of PAS2050 (BSI, 2008).

GHG emissions from livestock enteric fermentation, manure and urine were calculated according to the country specific, IPCC Tier 2 approach used in Australia's national GHG inventory (NGGIC, 2007), taking into account herd structure (on a daily time step; Section 3.1), feed quality and growth rates.

Emissions from agricultural soils as a result of inorganic nitrogen fertilizer application and the residue of cultivated leguminous pastures were also calculated following the method of the Australian national GHG inventory (NGGIC, 2007).

Land use change (deforestation) did not feature in any of the systems and possible changes in soil carbon were ignored due to a lack of relevant data.

The Australian Unit Process LCI (Grant, 2010), Australian environmental input-output data (Foran et al., 2005) and various CSIRO internal sources provided data on GHG emissions associated with fuels, fertilizers, supplementary feeds, veterinary and marketing services used on farm, fuels used to transport livestock between farms and to feedlots (where relevant), fuels used to deliver feed components to feedlots, and fuels, electricity and feed components consumed in feedlots.

To calculate the carbon footprint the latest 100-year global warming potentials for GHGs published by the IPCC were used (Forster and Ramaswamy, 2007, Table 2.14; See Appendix 9).

3.4 Life cycle impact assessment endpoint modelling

Damages to human health (Disability Adjusted Life Years, DALY) and ecosystem health (loss of species diversity, species.m^2.yr) due to GHG emissions were modeled using characterization factors reported by de Schryver et al. (2009), taking the Hierarchist cultural perspective. See Appendix 10.

The Hierarchist cultural perspective was chosen as the time horizon of 100 years corresponds with PAS 2050 (BSI, 2008) and draft ISO 14067, and because it presents a less extreme combination of value choices compared to the Individualist and Egalitarian perspectives.

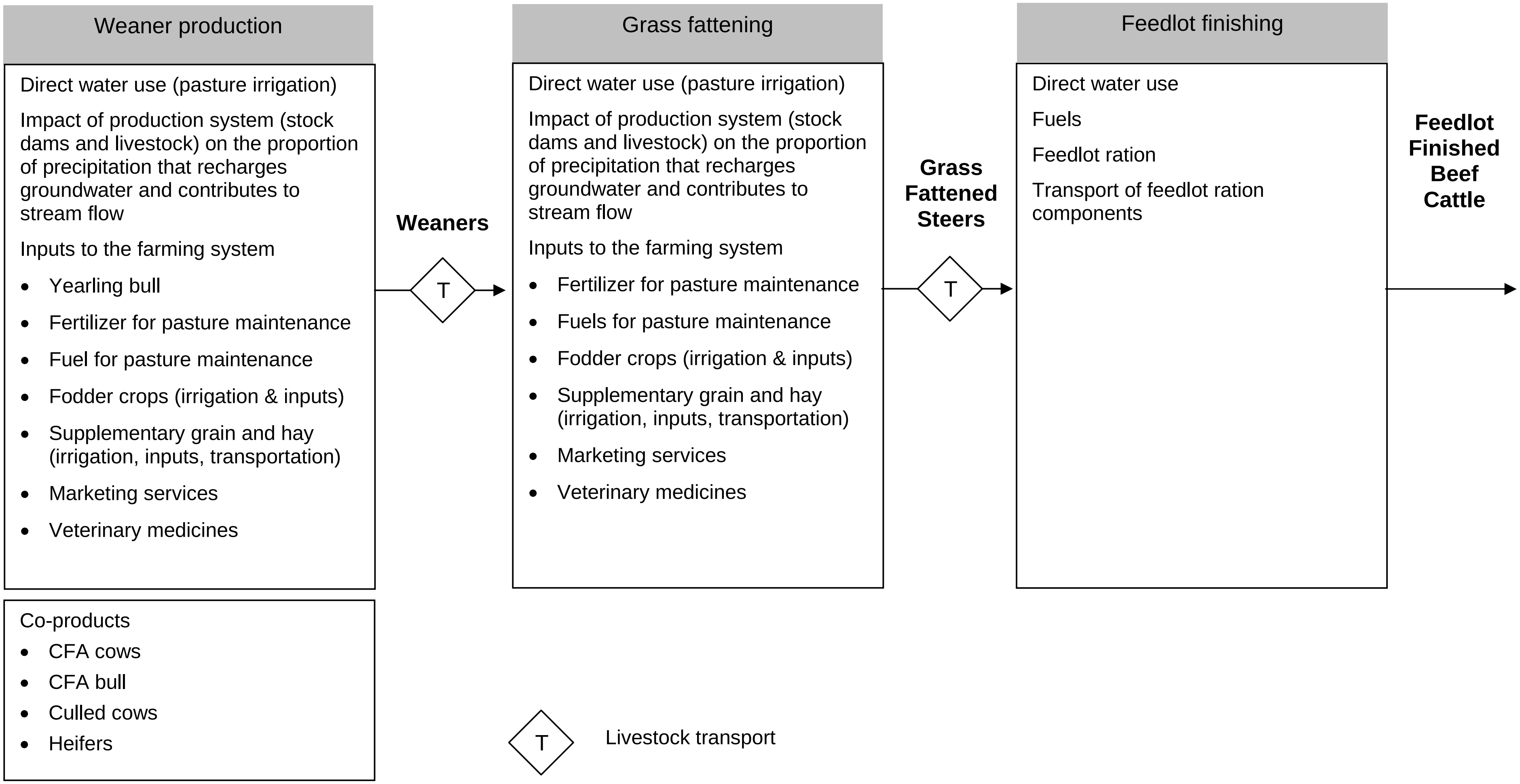
The Hierarchist cultural perspective was also used by Pfister et al. (2009), in the method adopted in this study to assess damages to human health, ecosystem health and depletion of resources (MJ) due to consumptive water use.

Using normalization factors and weights for the Hierarchist perspective taken from the Eco-indicator 99 life cycle impact assessment methodology (Goedkoop and Spriensma, 2000, p.113; See Appendix 11), aggregated scores were calculated (points/kg LW).

Damages arising from GHG emissions and water use were then compared.

of livestock

Figure 1. Example of a beef cattle supply chain showing components included in the water footprint modeling.



4 Results

4.1 Water footprint

For each geographically-defined beef cattle production system the consumptive water use and water footprint are shown in Table 6. Here, water use refers to the consumption of freshwater from ground and surface water resources as well as the volumetric impact on ground and surface water resources arising from the local storage and use of water in stock dams.

The water footprint results, expressed in the units H_2Oe, can be interpreted as follows: Each kg of live weight of yearling cattle produced in Bathurst exerts an equivalent pressure on freshwater systems as the direct consumption of 3.3 litres of water (at the global average WSI – Water Stress Index). It can be seen in these results, that the water footprint sometimes exceeds the volumetric water use and at other times is less, depending on the local water scarcity in the locations where water is consumed in each production system.

Table 6. Water use (L/kg LW) and water footprint (L H_2Oe/kg LW) for beef cattle at farm gate. Water use is defined in the text above.

Production system	Water use	Water footprint
Jap Ox (Scone)	234	14.4
EU cattle (Parkes)	53.5	68.3
Inland weaner, grass fattened and feedlot finished (Walgett, Gunnedah, Quirindi)	160	9.1
North coast weaner, grass fattened and feedlot finished (Casino, Glen Innes, Rangers Valley	139	7.7
Yearling (Gundagai)	167	221
Yearling (Bathurst)	24.7	3.3

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 Jap Ox relate only to a nominal Jap Ox production system located near Scone. The results cannot be used to describe Jap Ox production more generally in NSW or Australia. Also, the results may not accurately describe any specific Jap Ox-producing enterprise near Scone if the particular production system differs significantly from the nominal enterprise described in the NSW beef cattle enterprise budgets. In the same way, the results are not necessarily descriptive of any specific feedlot operation location in Quirindi or Rangers Valley. Rather, they relate to average feedlots (as defined by B.FLT.0350 and other data) nominally located in Quirindi and Rangers Valley.

These results, ranging from 3.3 to 221 L H_2Oe/kg live weight at farm gate, are an indication of the typical range of water footprint for beef cattle in NSW. While substantial variability exists in water footprint between individual cattle production systems, these results clearly demonstrate that many Australian beef cattle production systems exert very little pressure on freshwater systems from consumptive water use.

4.1.1 Variation in life cycle water use

Life cycle (cradle to farm gate) water use varied by almost a factor of 10 between the six case study beef production systems. Most of this variation related to the use of water to irrigate pasture, which ranged from 0 to 139 L/kg LW (Table 7). Water use in relation to the production of supplementary feed was another factor. Some systems required no supplementary feeds (Yearling-Bathurst, Yearling-Gundagai). For those systems that did utilise supplementary feeds, the use of irrigation was the differentiating factor.

In the feedlot subsystem, most of the water use was associated with production of the feed ration, especially the use of irrigation (Table 8).

Water use associated with the operation of local stock dams varied to a lesser extent (Table 7) and was related to the livestock drinking water demand and local evaporative losses from dams (Appendix 5-7).

Farm inputs and livestock transport were very minor sources of variation in water use (Table 7).

Table 7. Life cycle water use (L/kg LW) for beef cattle (cradle to farm gate). 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)

Production system	JO-S	EU-P	IGF	NGF	Y-G	Y-B
Irrigation of pasture	130	0	32.6	0	139	0
Stock dams and livestock watering	55.4	48.2	64.7	50.3	23.7	20.7
Replacement bull	0.3	0.3	0.4	0.3	0.2	0.2
Supplementary feed	47.2	1.8	2.4	0.5	0	0
Farm inputs (fuel, fertiliser, etc)	1.9	3.5	2.8	2.7	4.1	3.9
Feedlot finishing	0	0	57.2	85.1	0	0
Livestock transport	0	0	<0.1	<0.1	0	0
Total	234	53.4	160	139	167	24.7

Table 8. Water use (L/kg LW) in feedlot finishing. 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)

Production system	IGF (L/kg LW)	IGF (%)	NGF (L/kg LW)	NGF (%)
Direct water use	7.1	12	10.4	12
Fuels	0.1	<1	0.2	<1
Feed ration - irrigation	48.3	84	72.1	85
Feed ration - inputs	1.7	3	2.5	3
Feed ration – transport to feedlot	<0.1	<1	<0.1	<1
Total	57.2	100	85.1	100

4.1.2 Variation in water footprint

The major components contributing to the water footprint differed from one beef cattle production system to another (Table 9). It is therefore difficult to make generalisations, except that high water footprints will tend to be associated with beef cattle production systems which involve pasture irrigation in high water stress locations (e.g. Yearling – Gundagai in Table 9).

Table 9. Components that contributed to the life cycle (cradle to farm gate) water footprint for six geographically-defined beef cattle production systems. 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)

Production system	JO-S	EU-P	IGF	NGF	Y-G	Y-B
Irrigation of pasture (%)	46.6	0	12.3	0	84.3	0
Stock dams and livestock watering (%)	19.9	94.7	24.3	12.6	14.4	21.6
Replacement bull (%)	0.1	0.5	0.1	0.1	0.1	0.2
Supplementary feed (%)	24.8	1.8	9.7	4.7	0	0
Farm inputs (fuel, fertiliser, etc) (%)	8.5	3.1	20.0	23.2	1.2	78.2
Feedlot finishing (%)	0	0	33.5	59.4	0	0
Livestock transport (%)	0	0	<0.1	<0.1	0	0
Total (L H_2Oe/kg LW)	14.4	68.3	9.1	7.7	221	3.3

4.2 Carbon footprint

For the six beef cattle production systems in NSW, the carbon footprint (cradle to farm gate) ranged from 10.1 to 12.7 kg CO_2e/kg LW (Table 10). These results fall within the typical range reported internationally (i.e. about 6 to 20 kg CO_2e/kg LW). In extensive pastoral systems with lower productivity, the carbon footprint can exceed this range (e.g. 20 to 41 kg CO_2e/kg LW, Eady, 2011), and where significant deforestation occurs and this is counted in the carbon footprint calculation the results can be much larger again (e.g. > 350 kg CO2e/kg LW, Cederberg et al., 2011).

As expected, the carbon footprint was overwhelmingly influenced by methane emissions (Table 10), predominantly related to the livestock themselves (Table 11).

Compared to the water footprint, the differences in carbon footprint between the six production systems were small. That said, the beef cattle with the highest carbon footprint (12.7 kg CO_2e/kg LW, Table 10), came from a system where cows gave birth to their first calf at an average age of 36 months, compared to 24 months for the other systems (Table 4). Hence the importance of reproduction rate in the overall carbon footprint of beef cattle.

Table 10. Carbon footprint (CF, CO_2e/kg LW), and the contribution (%) of component greenhouse gases: methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2)

Production system	CF	CH_4	N_2O	CO_2
Jap Ox (Scone)	10.2	92.5	3.9	3.7
EU cattle (Parkes)	10.8	88.4	4.7	6.9
Inland weaner, grass fattened and feedlot finished (Walgett, Gunnedah, Quirindi)	10.1	87.2	3.9	8.9
North coast weaner, grass fattened and feedlot finished (Casino, Glen Innes, Rangers Valley)	12.7	88.0	3.7	8.3
Yearling (Gundagai)	10.4	87.5	4.3	8.1
Yearling (Bathurst)	10.6	88.6	4.3	7.1

Table 11. Components that contributed to the life cycle (cradle to farm gate) carbon footprint for six geographically-defined beef cattle production systems. 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)

Production system	JO-S	EU-P	IGF	NGF	Y-G	Y-B
Livestock emissions (%)	95.5	91.1	90.5	91.3	89.9	91.2
Fertilizer used on pastures (%)	1.8	5.0	1.4	1.2	5.8	5.1
Leguminous pastures (%)	0.4	0.9	0.3	0.1	0.7	0.6
Farm inputs (fuels, fertiliser, etc) (%)	1.3	2.9	1.4	1.1	3.6	3.2
Supplementary feeds used on farm (%)	0.9	0	1.0	0	0	0
Livestock transport (%)	0	0	0.2	0.1	0	0
Feedlot finishing (feed ration, energy, etc) (%)	0	0	5.3	6.2	0	0
Total (CO_2e/kg LW)	10.2	10.8	10.1	12.7	10.4	10.6

4.3 Comparing impacts from water use and GHG emissions

Regardless of the production system, potential damages from GHG emissions far exceeded potential damages from water use, with the former representing 94 to 98% of the combined Eco-indicator 99 scores. These results indicate, that for these case study beef cattle production systems, GHG emissions reduction should be a much higher priority that water use impact reduction.

Table 12. Potential damages to human health (DALY/kg LW), ecosystem quality (species.m^2.yr/kg LW) and resource depletion (MJ/kg LW) related to water use and GHG emissions in the life cycle (cradle to farm gate) of beef cattle production in NSW. Also shown are the aggregated scores after normalization and weighting (points/kg LW), and the fraction of combined damage related to GHG emissions (%): 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).

Production system	JO-S	EU-P	IGF	NGF	Y-G	Y-B
GHG emissions						
> Human health impacts	2.10E-06	2.26E-06	2.11E-06	2.65E-06	2.17E-06	2.22E-06
> Ecosystem impacts	2.19E+00	2.36E+00	2.19E+00	2.76E+00	2.26E+00	2.31E+00
> Aggregated score	2.25E-01	2.43E-01	2.26E-01	2.84E-01	2.33E-01	2.38E-01
Water use						
> Ecosystem impacts	1.00E-01	0.57E-01	1.99E-01	0.96E-01	1.74E-01	0.35E-01
> Resource depletion	1.12E-03	1.51E-03	1.77E-03	1.79E-03	1.25E-03	1.18E-03
> Aggregated score	0.78E-02	0.45E-02	1.56E-02	0.75E-02	1.36E-02	0.28E-02
GHG emission contribution to combined Eco-indicator 99 score	96.6	98.2	93.5	97.4	94.5	98.9

4.4 Land use inventory

The life cycle (cradle to farm gate) agricultural land use associated with the six beef cattle production systems varied from 64.0 to 121.1 m^2.yr/kg LW (Table 13). However, these totals should not be compared simplistically as they comprise different types of land in different locations. At this point in time, LCA methods which

Table 13. Agricultural land use[1] associated with six geographically-defined beef cattle production systems in NSW. 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).

	Land use m^2.yr/kg LW	Location	Total m^2.yr/kg LW
JO-S			121.1
Pasture-unimproved	93.6	Upper Hunter Shire (A) SLA	
Pasture-improved-not irrigated	21.1	Upper Hunter Shire (A) SLA	
Pasture-improved-irrigated	0.6	Upper Hunter Shire (A) SLA	
Cropland	5.8	Upper Hunter Shire (A) SLA	
EU-P			75.0
Pasture-unimproved	0	Parkes (A) SLA	
Pasture-improved-not irrigated	69.1	Parkes (A) SLA	
Pasture-improved-irrigated	0	Parkes (A) SLA	
Cropland	5.9	Parkes (A) SLA	
IGF			103.8
Pasture-unimproved	77.3	Walgett (A) SLA	
Pasture-improved-not irrigated	0.3	Walgett (A) SLA	
Pasture-improved-not irrigated	16.8	Gunnedah (A) SLA	
Pasture-improved-not irrigated	0.2	Northern SD	
Pasture-improved-irrigated	0.2	Gunnedah (A) SLA	
Pasture-improved-irrigated	<0.1	Northern SD	
Cropland	1.8	North western SD	
Cropland	2.1	Gunnedah (A) SLA	
Cropland	5.2	Northern SD	
Cropland	<0.1	Coastal QLD	
NGF			93.1
Pasture-unimproved	69.2	Richmond Valley (A) Bal SLA	
Pasture-improved-not irrigated	14.0	Glen Innes Severn (A) SLA	
Pasture-improved-not irrigated	0.3	Northern SD	
Pasture-improved-irrigated	<0.1	Northern SD	
Cropland	1.7	Glen Innes Severn (A) SLA	
Cropland	<0.1	Coastal QLD	
Cropland	7.8	Northern SD	
Y-G			64.0
Pasture-unimproved	0	Gundagai (A)	
Pasture-improved-not irrigated	62.9	Gundagai (A)	
Pasture-improved-irrigated	1.1	Gundagai (A)	
Cropland	0	Gundagai (A)	
Y-B			64.0
Pasture-unimproved	0	Bathurst Regional (A) - Pt B	
Pasture-improved-not irrigated	64.0	Bathurst Regional (A) - Pt B	
Pasture-improved-irrigated	0	Bathurst Regional (A) - Pt B	
Cropland	0	Bathurst Regional (A) - Pt B	

[1] The land use calculation does not include land use in the built environment (e.g. roads, factories), nor does it include land use associated with extraction of resources from nature (e.g. mining of phosphate, extraction of oil). These agricultural land use results are based on archetypal farm enterprise budgets (NSW I&I, 2010) and estimates of local agricultural yields obtained from ABS statistics.

express the environmental relevance of land use are still under development. This inventory of land use will be able to be used when such methods are available.

5 Discussion and conclusions

This study has produced new evidence concerning the environmental impact of consumptive water use in the livestock sector. The results, which are based on life cycle assessment including impact assessment, take into account both the quantity and the environmental relevance of water used, and are therefore consistent with the concept of a “water footprint” as defined in the draft international standard (ISO 14046).

For six geographically-defined case study production systems in NSW, chosen to be diverse in farm practice, product, environment and local water stress, the water footprint of the livestock ranged from 3.3 to 221 L H_2Oe/kg LW (at farm gate), which is similar to wheat, barley and oats grown in NSW (0.9 to 152 L H_2Oe/kg grain at farm gate; Ridoutt and Poulton, 2010).

This is not to exclude the possibility of higher water footprints where beef cattle production systems rely to a greater degree on irrigation, especially where irrigation is practiced in high water stress environments. Nevertheless, our results demonstrate that many low input, predominantly non-irrigated, pasture-based livestock production systems have little impact on freshwater resources from consumptive water use.

This is in sharp contrast to claims in the popular and academic media that livestock production is an important driver of global water scarcity (Pearce, 1997; Steinfeld et al., 2006; Liu et al., 2008; Marlow et al., 2009; Nellemann et al., 2009; Mekonnen and Hoekstra, 2010).

The wide range in water footprint results reported in this study (3.3 to 221 L H_2Oe/kg LW) also suggests that generalisations about the livestock industry need to be made with great care. The beef cattle livestock sector is not homogeneous in farm practice and geography, and claims about the water footprint of livestock and livestock products need to relate to a specific geographically-defined production system to be meaningful.

This study found that the environmental impacts of GHG emissions far exceeded those from water use and therefore GHG emissions reduction should continue to be a priority. Indeed, GHG emissions reductions which were achievable with a moderate increase in water footprint would probably lead to reduced overall environmental burden. Specific scenarios can now be evaluated using the modelling approach demonstrated in this project.

Considering water footprints alone, the most important opportunities for impact reduction include:

- Reducing the irrigation of pasture in high water stress environments
- Reducing evaporation from stock dams in high water stress environments
- Reducing the utilisation of supplementary feeds grown using irrigation in high water stress environments

However, it is necessary to emphasise that major strategic decisions should only be taken after considering all of the relevant environmental impacts as well as the broader triple bottom line concerns.

5.1 Industry benefits

5.1.1 Science-based evidence to support communication

At present, there are various claims being made about the water footprint of red meat products (e.g. 16,000 L/kg beef, www.waterfootprint.org; 50,000 to 100,000 L/kg beef, The Australian, Thursday October 2, 2008, p.13; 200,000 L/kg beef, Pimental et al., 1997). Water footprint values like these, calculated using a virtual water accounting approach, and which describe *volumes* rather than *impacts*, have the potential to mislead and confuse the community (Ridoutt et al., 2009) and to undermine the demand for and reputation of Australian beef in local and international markets.

Case study evidence has repeatedly shown that water footprints calculated using the virtual water accounting approach are not a reliable indicator of potential environmental impact (Ridoutt 2011). One product may have a higher virtual water content than another, but have lower environmental impacts from water use (Ridoutt and Pfister, 2010).

To our knowledge the results obtained in this study are the first to apply LCA-based water footprint calculation methods to beef cattle. These results are therefore novel, of high science value, and suitable for use by industry to advance the dialogue about the sustainability of livestock production from a water use perspective.

The water footprint calculation method applied in this study is consistent with the principles, guidelines and requirements described in the current draft international water footprint standard (ISO 14046).

The Australian and international beef cattle industry is therefore now in a better position to address poorly defined water footprint claims.

5.1.2 Prioritisation of environmental improvement efforts

For the range of beef cattle production systems represented in this study, it was found that environmental impacts from GHG emissions far outweighed impacts from consumptive water use.

Setting aside possible differences in abatement costs between carbon and water footprints (which were not assessed in this project), our findings suggest that, for beef cattle production systems of the kind represented by the case studies, GHG emissions reduction is a much higher priority for the industry than water footprint reduction, in order to lower overall environmental burden.

This study therefore offers science-based evidence to support priority setting for environmental improvement.

5.1.3 New capability to address carbon and water footprint tradeoffs

In practice, carbon and water footprints are interrelated in the sense that many of the possible interventions to reduce GHG emissions will also affect the water footprint. Naturally, an intervention that simultaneously reduced both the carbon and water footprints would be highly desirable (assuming there was not some other negative consequence); however, tradeoffs between the two are also possible. For example, to reduce livestock enteric methane emissions one very viable strategy is to improve forage quality, which can often be achieved through greater use of pasture irrigation and fertilization, actions which have the potential to raise water footprints. As such, the combined assessment of carbon and water footprints and the tradeoffs between the two is critical. This study has demonstrated an approach for such combined assessment which can now be used to evaluate environmental improvement scenarios for the beef cattle industry.

In addition, in the near future it is expected that combined assessment of environmental impacts from GHG emissions, water use and land use will be possible.

5.2 Recommendations for future action

5.2.1 National water footprint assessment

In this study the water footprints were calculated for beef cattle raised in six diverse livestock production systems. This research should be extended to enable a full national assessment to be completed. This will determine weather the conclusions reached in this study apply nationally and underpin more emphatic communication of the industry's performance with respect to consumptive water use. It will also identify any parts of the national beef cattle industry where water footprint reduction should be a priority. In addition, a national assessment will support national-level reporting to interested stakeholders.

5.2.2 Support the development of an international water footprint standard

It is in the interests of the Australian beef cattle industry that an international standard is created for water footprinting.

At the present time, the term "Water Footprint" is being used to mean different things in different contexts. This is creating confusion and misunderstanding which has the potential to 1) Harm the reputation of Australian products in local and international markets, and 2) Complicate the access of Australian exports to international value chains.

An international standard will provide consistency in use of the term "Water Footprint" and consistency in the method of calculating product Water Footprints so that comparability is possible. This will also lead to greater use of science-based evidence in the public and academic dialogue about the role of meat in a sustainable global food system.

5.2.3 Support the multi-indicator approach to agri-food environmental assessment

Individual environmental indicators, such as the carbon footprint and water footprint, do not, on their own, provide an indication of overall environmental impact. This is especially important for the agri-food sector where impacts from GHG emissions, water use and land use can all be important and tradeoffs are common. A balanced assessment requires combined assessment and this kind of approach should be supported by the beef cattle industry in Australia.

Appendix 1: Farm enterprise budgets

The following farm enterprise budgets developed by the NSW government (NSW I&I, 2010) are for beef cattle production systems in NSW with a nominal 100 cows at the commencement of joining.

Enterprise	Japanese Ox – grass-fed steers	
Income	33 steers, @ 24-30 months, 340 kg DW	$36,465
	8 steers, @ 36 months, 340 kg DW	$8,677
	22 heifer yearling @ 16-18 months, 200 kg DW	$13,200
	1 CFA bull, 450 kg DW	$1,125
	7 CFA cows, 240 kg DW	$4,704
	12 other culls, 240 kg DW	$8,064
Variable costs	Replacement bull (run at 3%, sold after 4 years)	$5,000
	Livestock and veterinary costs	$1,684
	Fodder crops (20 ha)	$3,000
	Supplementary feed	$2,000
	Pasture maintenance	$4,600
	Livestock selling costs	$2,626
Assumptions	Weaning rate: 86%	
	Conception rate: 92%	
	Mortality rate of adult stock: 2%	
	Cows: age at first calf: 24 months	
	Heifers retained for replacement: 20	

Enterprise	EU cattle	
Income	34 steers, @ 26 months, 300 kg DW	$34,170
	8 steers, @ 24-30 months, 280 kg DW	$7,347
	18 heifers @ 20-24 months, 270 kg DW	$15,552
	4 heifers @ 20 months, 240 kg DW	$3,014
	1 CFA bull, 450 kg DW	$1,125
	7 CFA cows, 240 kg DW	$4,704
	11 other culls, 240 kg DW	$7,392
Variable costs	Replacement bull (run at 3%, sold after 4 years)	$5,000
	Livestock and veterinary costs	$1,403
	Fodder crops (25 ha)	$3,750
	Supplementary feed	$2,000
	Pasture maintenance	$14,750
	Livestock selling costs	$3,214
Assumptions	Weaning rate: 86%	
	Mortality rate of adult stock: 2%	
	Cows: age at first calf: 24 months	
	Heifers retained for replacement: 20	

Enterprise	Inland weaners	
Income	42 steer weaners, @ 9 months, 260 kg LW	$21,294
	21 heifer weaners @ 9 months, 230 kg LW	$8,694
	1 CFA bull, 405 kg DW	$1,013
	6 CFA cows, 230 kg DW	$3,726
	13 other culls, 230 kg DW	$8,073
Variable costs	Replacement bull (run at 3%, sold after 4 years)	$4,500
	Livestock and veterinary costs	$1,036
	Fodder crops	$0
	Supplementary feed	$2,400
	Pasture maintenance	$0
	Livestock selling costs	$2,868
Assumptions	Weaning rate: 84%	
	Conception rate: 90%	
	Mortality rate of adult stock: 2%	
	Cows: age at first calf: 24 months	
	Heifers retained for replacement: 21	

Enterprise	Growing out steers for feedlot market	
Income	98 steers, @ 21 months, 420 kg LW	$80,094
Variable costs	Steer purchase (100 @ 9 months, 240 kg LW)	$48,000
	Cartage to property	$1,000
	Livestock and veterinary costs	$926
	Fodder crops (12 ha)	$1,800
	Supplementary feed	$0
	Pasture maintenance	$4,850
	Livestock selling costs	$5,156
Assumptions	Steers kept for 12 months	
	Mortality rate of adult stock: 2%	

Enterprise	North coast weaners	
Income	32 steer weaners @ 7 months, 160 kg LW	$9,728
	13 heifer weaners @ 7 months, 130 kg LW	$2,958
	1 CFA bull, 324 kg DW	$810
	11 CFA cows, 180 kg DW	$4,950
	3 other culls, 180 kg DW	$1,350
Variable costs	Replacement bull (run at 3%, sold after 5 years)	$3,500
	Livestock and veterinary costs	$1,639
	Fodder crops	$0
	Supplementary feed	$0
	Pasture maintenance	$0
	Livestock selling costs	$1,758
Assumptions	Weaning rate: 64%	
	Mortality rate of adult stock: 4%	
	Cows: age at first calf: 36 months	
	Heifers retained for replacement: 19	

Enterprise	Growing out early weaned calves	
Income	98 steers, @ 18 months, 340 kg LW	$61,506
Variable costs	Steer purchase (100 @ 6 months, 160 kg LW)	$32,800
	Cartage to property	$1,000
	Livestock and veterinary costs	$926
	Fodder crops (10 ha)	$1,500
	Supplementary feed	$0
	Pasture maintenance	$4,000
	Livestock selling costs	$3,957
Assumptions	Steers kept for 12 months	
	Mortality rate of adult stock: 2%	

Enterprise	Yearling (Southern/Central NSW)	
Income	42 steers @ 12-15 months, 205 kg DW	$26,261
	22 heifers @ 12-15 months, 185 kg DW	$12,617
	1 CFA bull, 432 kg DW	$1,125
	7 CFA cows, 255 kg DW	$4,704
	11 other culls, 255 kg DW	$8,064
Variable costs	Replacement bull (run at 3%, sold after 4 years)	$5,000
	Livestock and veterinary costs	$1,203
	Fodder crops	$0
	Supplementary feed	$0
	Pasture maintenance	$10,550
	Livestock selling costs	$4,279
Assumptions	Weaning rate: 86%	
	Conception rate: 92%	
	Mortality rate of adult stock: 2%	
	Cows: age at first calf: 24 months	
	Heifers retained for replacement: 20	

Appendix 2: Irrigation of improved pasture

Irrigation of improved pasture (excluding dairy) and rate of irrigation water use in locations of relevance to this study. Source ABS (2008, 2009) and Khan et al. (2010).

Location	Statistical Local Area	Irrigation of improved pasture (%)	Rate of irrigation (ML/ha)
Scone	Upper Hunter Shire	2.3	2.6
Parkes	Parkes	0	0
Gunnedah	Gunnedah	1.0	2.0
Glen Innes	Glen Innes Severn	0	0
Gundagai	Gundagai	1.7	1.3
Bathurst	Bathurst Regional	0	0

Appendix 3: Pasture growth and quality

Pasture growth, digestibility and moisture content data for locations of relevance to the case studies. The moisture content of grazing oats was assumed to be 85% and the moisture content of conserved fodder, grain and hay 10%. Source: GrassGro® (www.grazplan.csiro.au) and New_LocClim local climate estimator (FAO, 2005).

Bathurst

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	20.0	19.6	17.2	13.0	9.1	6.4	5.1	6.8	9.1	12.5	15.3	18.2
Rainfall (mm)	79	60	54	49	49	34	45	58	49	62	58	63
Pasture growth (kg/ha/d)	16.8	12.4	16.6	19.4	16.2	6.8	4.7	7.3	19.5	46.8	53.2	38.1
Digestibility (g/g)	0.68	0.65	0.66	0.70	0.73	0.74	0.74	0.75	0.75	0.76	0.75	0.73
MC (%)	55.7	50.3	51.7	62.0	67.7	70.4	71.3	71.8	73.0	74.6	72.0	67.1

Parkes

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	24.7	24.3	21.7	17.3	13.0	9.8	8.8	10.3	13.1	16.8	20.2	23.2
Rainfall (mm)	78	53	52	53	64	36	50	57	42	62	55	55
Pasture growth (kg/ha/d)	11.4	11.8	9.3	10.4	12.6	9.5	8.1	8.1	15.4	30.3	19.6	13.0
Digestibility (g/g)	0.61	0.59	0.60	0.64	0.70	0.73	0.73	0.73	0.73	0.72	0.68	0.64
MC (%)	40.3	34.5	37.5	48.2	61.4	67.0	68.6	69.1	68.5	66.4	56.8	48.0

Casino

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	24.7	24.5	23.2	20.6	17.3	14.8	13.6	15.0	17.7	20.2	22.5	23.8
Rainfall (mm)	136	174	161	105	96	70	64	42	33	78	86	134
Pasture growth (kg/ha/d)	37.1	55.1	53.7	32.4	15.1	6.9	2.5	2.5	7.7	15.3	21.5	28.9
Digestibility (g/g)	0.66	0.67	0.68	0.69	0.69	0.68	0.64	0.60	0.59	0.60	0.64	0.65
MC (%)	52.9	53.5	55.6	57.6	59.4	56.4	46.3	38.1	34.7	38.3	47.1	50.6

Scone

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	23.7	23.2	21.2	17.8	14.1	11.3	10.3	11.8	14.6	17.7	20.2	23.0
Rainfall (mm)	87	78	52	41	50	42	36	40	40	61	56	68
Pasture growth (kg/ha/d)	24.2	22.0	16.9	11.5	7.9	6.4	7.1	10.4	19.7	28.0	24.7	22.2
Digestibility (g/g)	0.60	0.58	0.57	0.58	0.62	0.66	0.69	0.70	0.70	0.70	0.67	0.63
MC (%)	37.1	32.4	29.9	32.9	43.0	52.7	58.8	61.4	61.7	60.0	55.2	43.7

Gunnedah

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	25.5	25.2	23.1	19.1	14.6	11.3	10.0	11.6	14.8	18.7	21.3	24.2
Rainfall (mm)	100	65	48	42	54	36	44	41	39	59	63	72
Pasture growth (kg/ha/d)	24.2	22.0	16.9	11.5	7.9	6.4	7.1	10.4	19.7	28.0	24.7	22.2
Digestibility (g/g)	0.60	0.58	0.57	0.58	0.62	0.66	0.69	0.70	0.70	0.70	0.67	0.63
MC (%)	37.1	32.4	29.9	32.9	43.0	52.7	58.8	61.4	61.7	60.0	55.2	43.7

Glen Innes

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	19.8	19.7	18.0	14.8	11.0	8.1	6.9	8.1	10.8	14.1	16.7	19.0
Rainfall (mm)	123	86	74	52	63	45	60	57	63	79	92	122
Pasture growth (kg/ha/d)	33.4	35.7	36.4	24.0	9.2	6.0	6.0	7.8	18.1	35.9	43.1	41.7
Digestibility (g/g)	0.68	0.64	0.64	0.72	0.76	0.79	0.80	0.81	0.80	0.80	0.78	0.74
MC (%)	55.2	46.0	47.1	64.6	75.1	80.9	84.4	86.7	84.4	84.4	80.0	70.4

Gundagai

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	21.7	22.1	19.0	14.1	10.5	7.5	6.5	8.3	10.6	13.8	16.6	19.7
Rainfall (mm)	61	41	50	71	82	62	91	94	77	87	60	63
Pasture growth (kg/ha/d)	6.2	6.1	10.4	19.7	19.5	11.0	8.6	17.5	32.9	49.4	33.1	10.9
Digestibility (g/g)	0.60	0.57	0.58	0.63	0.72	0.77	0.78	0.79	0.79	0.78	0.70	0.65
MC (%)	37.8	29.6	32.0	44.8	64.6	77.4	80.0	82.1	82.1	80.0	61.1	48.3

Walgett

Month	J	F	M	A	M	J	J	A	S	O	N	D
Mean Temp (°C)	28.1	27.7	25.2	20.7	16.0	12.3	11.3	13.1	16.7	20.7	24.1	27.1
Rainfall (mm)	84	48	43	44	48	23	34	35	29	38	40	42
Pasture growth (kg/ha/d)	15.0	20.0	17.0	9.0	3.0	1.0	1.0	3.0	9.0	17.0	18.0	14.0
Digestibility (g/g)	0.69	0.69	0.67	0.60	0.54	0.50	0.50	0.60	0.69	0.69	0.69	0.69
MC (%)	58.8	58.8	54.1	36.6	23.8	14.5	14.5	37.8	57.6	58.8	58.8	58.8

Appendix 4: Beef cattle dry matter intake

Seasonal live weight (kg/head), live weight gain (kg/head/day) and dry matter intake (kg DM/head/day) for beef cattle in NSW. Source: NGGIC (2007). Adjustments were made for grass fattening operations to balance initial and final livestock weights.

Live weight

Season	Bulls SRW	Steers <1	Steers >1	Steers >2	Cows <1	Cows >1	Cows >2	Cows SRW	Cows Lactating
Spring	700	75	380	570	75	300	440	500	
Summer	700	160	420	610	160	360	470	500	
Autumn	700	220	450	640	220	390	490	500	
Winter	700	260	460	650	260	410	500	500	

Live weight gain

Season	Bulls SRW	Steers <1	Steers >1	Steers >2	Cows <1	Cows >1	Cows >2	Cows SRW	Cows Lactating
Spring	0	0.5	0.4	0.4	0.5	0.4	0.3	0	
Summer	0	0.9	0.4	0.4	0.9	0.7	0.3	0	
Autumn	0	0.7	0.3	0.3	0.7	0.3	0.2	0	
Winter	0	0.4	0.1	0.1	0.4	0.2	0.1	0	

Dry matter intake

Season	Bulls SRW	Steers <1	Steers >1	Steers >2	Cows <1	Cows >1	Cows >2	Cows SRW	Cows Lactating
Spring	9.5	2.8	7.1	9.3	2.8	5.9	7.7	7.9	10.2
Summer	9.5	4.5	7.6	9.7	4.5	7.3	8.1	7.9	8.7
Autumn	9.5	5.2	7.8	9.7	5.2	7.0	8.1	7.9	7.9
Winter	9.5	5.4	7.6	9.4	5.4	7.1	8.0	7.9	7.9

Appendix 5: Monthly livestock water budgets

Drinking water requirement (L/head/day) for beef cattle in locations of relevance to the case studies. Source: Calculations based on data in CSIRO (2007).

Bathurst

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	29.3	30.9	25.3	17.8	13.4	10.8	9.7	9.1	7.6	5.4	8.8	18.1
Steer, < 1 year old	9.9	10.7	11.8	6.9	1.5	0	0	0	0	0	0	4.6
Steer, 1-2 year old	23.4	24.6	20.7	10.3	2.2	0	0	0	0	0	5.5	14.4
Steer, > 2 year old	29.8	31.4	25.8	12.9	2.8	0	0	0	0	0	7.2	18.4
Cow, < 1 year old	9.9	10.7	11.8	6.9	1.5	0	0	0	0	0	0	4.6
Cow, 1-2 year old	22.4	23.6	18.7	9.3	2.0	0	0	0	0	0	4.6	13.9
Cow, SRW, Dry	31.0	32.1	26.7	15.1	6.0	0.7	0	0	1.2	4.1	11.4	21.1
Cow, SRW, Lactating	38.1	39.4	28.7	15.1	6.0	0.7	0	0	7.6	11.3	20.8	27.2

Parkes

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	48.5	48.4	41.0	29.1	18.2	10.0	8.2	8.9	12.6	15.9	29.3	40.6
Steer, < 1 year old	19.0	19.0	20.3	15.8	7.1	0.2	0	0	0	0	2.6	15.3
Steer, 1-2 year old	38.7	38.6	33.6	23.8	10.7	0.2	0	0	5.6	11.8	21.8	32.4
Steer, > 2 year old	49.2	49.1	41.8	29.7	13.3	0.3	0	0	7.4	15.6	28.7	41.2
Cow, < 1 year old	19.0	19.0	20.3	15.8	7.1	0.2	0	0	0	0	2.6	15.3
Cow, 1-2 year old	37.1	37.0	30.3	21.5	9.6	0.2	0	0	4.7	9.9	18.3	31.1
Cow, SRW, Dry	48.8	48.5	41.3	29.9	15.4	4.1	1.4	3.9	10.9	18.9	31.1	41.6
Cow, SRW, Lactating	57.7	57.4	43.3	29.9	15.4	4.1	1.4	3.9	20.2	30.5	46.4	49.8

Casino

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	42.9	42.1	37.4	29.8	21.8	21.1	25.2	27.5	31.4	36.0	39.0	41.3
Steer, < 1 year old	16.4	16.0	18.4	16.2	11.8	10.6	11.7	14.4	3.2	4.5	5.4	15.6
Steer, 1-2 year old	34.3	33.6	30.7	24.4	17.8	14.9	16.6	20.4	23.3	26.7	29.0	32.9
Steer, > 2 year old	43.6	42.7	38.2	30.4	22.2	18.5	20.6	25.3	30.7	35.2	38.2	41.9
Cow, < 1 year old	16.4	16.0	18.4	16.2	11.8	10.6	11.7	14.4	3.2	4.5	5.4	15.6
Cow, 1-2 year old	32.9	32.2	27.6	22.0	16.1	14.1	15.6	19.2	19.6	22.4	24.3	31.6
Cow, SRW, Dry	44.2	43.4	39.0	31.7	23.8	20.6	22.0	26.3	31.9	36.6	40.0	42.5
Cow, SRW, Lactating	52.7	51.8	41.0	31.7	23.8	20.6	22.0	26.3	47.5	53.5	58.0	50.7

Scone

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	45.1	44.8	40.7	32.7	23.8	20.3	17.5	16.5	18.0	22.2	30.1	41.4
Steer, < 1 year old	17.4	17.3	20.1	17.8	11.1	7.1	4.7	5.4	0	0.5	2.8	15.7
Steer, 1-2 year old	36.0	35.8	33.3	26.8	16.7	10.0	6.7	7.6	11.4	16.5	22.3	33.1
Steer, > 2 year old	45.8	45.5	41.5	33.3	20.7	12.4	8.3	9.4	15.1	21.7	29.4	42.1
Cow, < 1 year old	17.4	17.3	20.1	17.8	11.1	7.1	4.7	5.4	0	0.5	2.8	15.7
Cow, 1-2 year old	34.6	34.3	30.0	24.1	15.0	9.4	6.3	7.1	9.6	13.8	18.8	31.7
Cow, SRW, Dry	45.6	45.1	40.8	33.0	21.7	14.6	10.9	12.2	17.8	24.3	31.7	42.2
Cow, SRW, Lactating	54.2	53.6	42.8	33.0	21.7	14.6	10.9	12.2	29.1	37.6	47.3	50.5

Gunnedah

Month	J	F	M	A	M	J	J	A	S	O	N	D
Steer, < 1 year old						4.9	2.2	3.6				
Steer, 1-2 year old	41.8	41.9	37.9	29.3	14.3				8.9	16.8	25.2	37.1

Glen Innes

Month	J	F	M	A	M	J	J	A	S	O	N	D
Steer, < 1 year old			15.9	7.6	0	0	0	0				
Steer, 1-2 year old	23.5	26.3							0	0	0	13.3

Gundagai

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	39.7	42.5	34.7	25.7	16.0	0.7	0	0	0	0	19.4	31.8
Steer, < 1 year old	14.8	16.2	16.9	12.1	3.9	0	0	0	0	0	0	11.1
Steer, 1-2 year old	31.7	33.9	28.4	18.2	5.9	0	0	0	0	0	14.4	25.4
Steer, > 2 year old	40.3	43.1	35.4	22.7	7.3	0	0	0	0	0	18.9	32.3
Cow, < 1 year old	14.8	16.2	16.9	12.1	3.9	0	0	0	0	0	0	11.1
Cow, 1-2 year old	30.4	32.5	25.6	16.4	5.3	0	0	0	0	0	12.1	24.4
Cow, SRW, Dry	40.2	42.7	35.1	23.2	10.0	0	0	0	0	0	21.6	33.0
Cow, SRW, Lactating	48.2	51.0	37.1	23.2	10.0	0	0	0	0	3.6	34.1	40.3

Walgett

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	51.1	49.7	43.9	37.8	30.7	31.9	31.8	27.6	21.6	29.4	38.3	47.6
Steer, < 1 year old	20.2	19.6	21.9	20.6	16.6	14.4	13.5	12.7	0.3	2.6	5.2	18.6
Steer, 1-2 year old	40.7	39.6	36.0	31.0	25.0	20.4	19.1	17.9	16.0	21.8	28.4	38.0
Steer, > 2 year old	51.9	50.4	44.8	38.6	31.1	25.3	23.7	22.3	21.1	28.8	37.4	48.3
Cow, < 1 year old	20.2	19.6	21.9	20.6	16.6	14.4	13.5	12.7	0.3	2.6	5.2	18.6
Cow, 1-2 year old	39.1	38.0	32.4	27.9	22.5	19.2	18.0	16.9	13.5	18.4	23.9	36.5
Cow, SRW, Dry	52.8	51.4	45.3	38.3	30.6	25.6	24.1	23.3	23.5	31.4	40.1	49.4
Cow, SRW, Lactating	62.1	60.5	47.3	38.3	30.6	25.6	24.1	23.3	36.5	46.8	58.2	58.3

Appendix 6: Herd structure

Monthly tallies of livestock x days for the case study beef cattle production systems (i.e. 3 bulls on the farm for every day in January = 3 x 31 = 93 livestock days).

Bathurst

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	93	84	70	68	70	68	70	70	68	93	90	93
Steer, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Steer, 1-2 year old	0	0	0	0	0	0	0	0	588	1277	428	101
Steer, > 2 year old	0	0	0	0	0	0	0	0	0	0	0	0
Cow, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Cow, 1-2 year old	0	0	0	0	0	0	0	0	588	1297	1028	221
Cow, SRW, Dry	651	588	501	951	2143	2610	2697	2697	1888	633	30	531
Cow, SRW, Lactating	2666	2408	2634	1764	554	0	0	0	722	2064	2580	2666

Parkes

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	93	84	70	68	70	68	70	70	68	93	90	93
Steer, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Steer, 1-2 year old	1302	1176	1302	1260	1302	1260	1302	1302	1260	1302	1260	1302
Steer, > 2 year old	55	0	0	0	0	0	0	0	588	1302	958	402
Cow, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Cow, 1-2 year old	682	616	682	660	640	557	377	116	588	1302	1260	802
Cow, SRW, Dry	651	588	501	951	2143	2610	2697	2697	1888	633	30	531
Cow, SRW, Lactating	2666	2408	2634	1764	554	0	0	0	722	2064	2580	2666

Casino

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	93	84	74	72	74	72	74	74	72	93	90	93
Steer, < 1 year old	992	896	992	672	211	0	0	0	269	768	960	992
Steer, 1-2 year old												
Steer, > 2 year old												
Cow, < 1 year old	992	896	976	921	763	540	558	558	557	768	960	992
Cow, 1-2 year old	558	504	558	540	558	540	558	558	540	558	540	558
Cow, SRW, Dry	1457	1316	1375	1632	2467	2790	2883	2883	2504	1905	1410	1457
Cow, SRW, Lactating	1984	1792	1968	1323	416	0	0	0	538	1536	1920	1984

Scone

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	93	84	70	68	70	68	70	70	68	93	90	93
Steer, < 1 year old	1333	1204	1301	1230	1271	1230	1271	1271	1017	1032	1290	1333
Steer, 1-2 year old	1271	1148	1271	1230	1271	1230	1271	1271	1230	1271	1230	1271
Steer, > 2 year old	471	230	254	246	254	246	254	254	746	1325	1230	956
Cow, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Cow, 1-2 year old	682	548	277	0	0	0	0	0	588	1302	1260	802
Cow, SRW, Dry	651	588	517	972	2149	2610	2697	2697	1888	633	30	531
Cow, SRW, Lactating	2666	2408	2618	1743	548	0	0	0	722	2064	2580	2666

Gunnedah

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW												
Steer, < 1 year old	0	0	0	0	0	0	3100	3100	2160	700	0	0
Steer, 1-2 year old	3038	2744	3038	2940	3038	2940	0	0	840	2400	3000	3100
Steer, > 2 year old												
Cow, < 1 year old												
Cow, 1-2 year old												
Cow, SRW, Dry												
Cow, SRW, Lactating												

Glen Innes

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW												
Steer, < 1 year old	0	0	0	0	3100	3000	3100	3100	2160	700	0	0
Steer, 1-2 year old	3038	2744	3038	2940	0	0	0	0	840	2400	2940	3038
Steer, > 2 year old												
Cow, < 1 year old												
Cow, 1-2 year old												
Cow, SRW, Dry												
Cow, SRW, Lactating												

Gundagai

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	93	84	70	68	70	68	70	70	68	93	90	93
Steer, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Steer, 1-2 year old	0	0	0	0	0	0	0	0	588	1277	428	101
Steer, > 2 year old	0	0	0	0	0	0	0	0	0	0	0	0
Cow, < 1 year old	1333	1204	1317	1260	1302	1260	1302	1302	1033	1032	1290	1333
Cow, 1-2 year old	0	0	0	0	0	0	0	0	588	1297	1028	221
Cow, SRW, Dry	651	588	501	951	2143	2610	2697	2697	1888	633	30	531
Cow, SRW, Lactating	2666	2408	2634	1764	554	0	0	0	722	2064	2580	2666

Walgett

Month	J	F	M	A	M	J	J	A	S	O	N	D
Bull SRW	93	84	70	68	70	68	70	70	68	93	90	93
Steer, < 1 year old	1302	1176	1302	1260	1302	882	277	0	353	1008	1260	1302
Steer, 1-2 year old												
Steer, > 2 year old												
Cow, < 1 year old	1302	1176	1302	1260	1302	1197	928	651	689	1008	1260	1302
Cow, 1-2 year old	0	0	0	0	0	0	0	0	294	651	630	126
Cow, SRW, Dry	682	616	472	876	2081	2550	2635	2635	1844	619	30	556
Cow, SRW, Lactating	2604	2352	2604	1764	554	0	0	0	706	2016	2520	2604

Appendix 7: Farm dam extractions and evaporation

Annual farm dam extractions (ML) and losses due to evaporation (ML) for the case study production systems. A demand factor of 0.5 is assumed (extractions as a proportion of total dam capacity) as well as a storage factor of 0.6 (average volume in storage as a proportion of total dam capacity).

Location	Extractions	Evaporation	Total use
Bathurst	0.86	0.29	1.15
Parkes	1.86	0.75	2.60
Casino	1.70	0.67	2.37
Scone	2.11	0.83	2.93
Gunnedah	0.85	0.37	1.22
Glen Innes	0.29	0.10	0.39
Gundagai	0.92	0.34	1.27
Walgett	1.73	0.83	2.56

Appendix 8: Farm water balances

Farm water balances for the case study production systems.

Bathurst

Location	Bathurst	Parkes	Casino	Scone	Gunnedah	Glen Innes	Gundagai	Walgett
Farm land area (ha/year)	211	295	254	492	97	80	211	372
Rainfall (mm/year)	635	584	1096	645	619	849	713	477
Base scenario								
ET (mm/year)	485	459	659	490	477	578	522	397
Drainage/Runoff (mm/year)	150	125	437	155	142	271	191	80
Drainage/Runoff (ML/farm)	317	370	1110	763	138	216	403	298
Scenario with farm dams								
Extractions (ML/farm)	0.86	1.86	1.70	2.11	0.85	0.29	0.92	1.73
Evaporation (ML/farm)	0.29	0.75	0.67	0.83	0.37	0.10	0.34	0.83
Urine return (ML/farm)	0.94	1.17	0.75	1.12	0.53	0.57	0.88	0.66
ET (mm/year)	485	459	659	490	477	578	522	397
Drainage/Runoff (ML/farm)	316	368	1108	761	137	216	402	295
Difference (ML/farm)	0.68	2.06	1.83	2.37	0.96	0.03	0.78	2.31

Appendix 9: 100-year global warming potentials

100-year global warming potentials (GWP, CO_2e) for GHGs relevant to this study (Forster and Ramaswamy, 2007, Table 2.14).

GHG	GWP
CO_2	1
CH_4	25
N_2O	298

Appendix 10: Endpoint characterisation factors

Characterization factors for damage to human health (DALY/kton) and ecosystems (species.km^2.yr/kton) due to greenhouse gas emissions of relevance to this study (de Schryver et al., 2009).

GHG	Human Health	Ecosystems
CO_2	2.55E-01	2.66E-01
CH_4	5.04E+00	5.25E+00
N_2O	8.33E+01	8.68E+01

Appendix 11: Normalization factors and weights

Normalization factors and weights for the Hierarchist cultural perspective (Goedkoop and Spriensma, 2000).

	Normalisation	Weights
Human Health	1.54E-02	400
Ecosystem Quality	5.13E+03	400
Resources	8.41E+03	200

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