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Resource use and environmental impacts from Australian chicken meat production

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ABSTRACT

Agri-food industries such as chicken meat production face increasing pressure to quantify and improve their environmental performance over time, while simultaneously increasing production to meet global demand. Using life cycle assessment, this study aimed to quantify resource use, environmental impacts and hotspots for Australian chicken meat production using updated inventories and new methods. Two contrasting states; Queensland, and South Australia, and two housing systems; conventional and free range were analysed to indicate the variation expected between regions and systems. Lower impacts were observed per kilogram of chicken meat produced in South Australia compared to Queensland for fossil fuel energy, greenhouse gas (including land use and direct land use change) and fresh water consumption (18.1 and 21.4 MJ, 2.8 and 3.4 kg CO_2-e, 38 and 111 L respectively), but not arable land or stress weighted water use (22.5 and 14 m^2, 36 and 26 L H_2O-e respectively). Feed production was the largest contributor to all impact categories, and also showed the largest variation between regions, highlighting the importance of spatially specific feed grain datasets to determine resource use and greenhouse gas from chicken meat production. While the feed conversion ratio was lower in South Australia, this was found to be less significant than differences related to crop yield, irrigation water use and the use of imported feed ingredients, suggesting that incremental improvements in feed conversion ratio will result in lower impacts only when feed inputs and production systems do not change. Fresh water consumption was lower in South Australia, but did not correlate with stress weighed water use (lower in Queensland), highlighting that volumetric water use is not a reliable indicator of the impact of water use. We did not observe substantial differences between conventional and free range production when feed related differences were removed, because key productivity factors such as feed conversion ratio were similar between the two housing types in Australia. While results were found to vary between regions, total greenhouse gas emissions were low from these Australian supply chains, and resource use was moderate. Expansion of the study to include additional regions and impact categories is recommended in future benchmarking studies.

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1. Introduction

Food production supply chains face increasing pressure over the utilisation of scarce resources and the generation of environmentally relevant emissions, and global initiatives have been initiated to benchmark the impact of livestock supply chains on climate change (MacLeod et al., 2013) and other impacts. Life cycle assessment (LCA) has been widely used to benchmark the environmental performance of supply chains globally. However, the lack of internationally agreed methods can make comparison difficult (De Vries and De Boer, 2010.). In Australia, a series of studies investigating regional or national livestock production systems, using broadly comparable methods, have been completed by the authors and others. These studies include regional beef and lamb production (Ridoutt et al., 2012; Wiedemann et al., 2015b) and pork production (Wiedemann et al., 2016a). These studies provide a regional knowledge base for understanding the environmental impact of Australian meat production, but there is a need for more studies focussing on poultry production. Future increases in global demand for grain and meat (FAO, 2009) are expected to result in greater pressure on water and arable land. Most LCA research in Australia has focussed on greenhouse gas

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(GHG) emissions and this is an acknowledged issue of global significance. Because in Australia water is a scarce and heavily allocated resource (MDBA, 2012) and arable land represents only a small fraction of the total land mass available (Lesslie and Mewett, 2013), and further research is needed in these areas.

The Australian chicken meat industry is vertically integrated with modern, efficient production systems that aim to maximise the environmental efficiency of their production systems. Feed conversion ratio in chicken meat production is low relative to other species, resulting in lower impacts via feed production. Because of the controlled nature of production, where most birds are housed in-doors, the direct impacts are also minimised. However, few data are available to quantify the performance of the industry or the contribution of impacts from each stage in the supply chain. One study (Bengtsson and Seddon, 2013) investigated the impacts of chicken meat production from a large, vertically integrated company in Australia, and a number of chicken meat LCAs have been completed elsewhere in the world (i.e. Leinonen et al., 2012; Pelletier, 2008). These studies highlight the significance of feed production as a major contributor to GHG and nutrient related impacts from chicken meat production, though in most cases a comprehensive assessment of primary resources, viz; energy, water and land was not included. These studies have shown that GHG impacts from chicken meat arise predominantly from soil nitrous oxide and fossil fuel use in crop production and housing, and manure related emissions. Most chicken meat studies (i.e. Leinonen et al., 2012; Pelletier, 2008; Williams et al., 2006) did not include impacts from meat processing, even where results are reported on a carcase weight (CW) basis, and consequently, energy and water use from this stage may have been underestimated. Because of the low input nature of Australian grain production and predominantly dry soil conditions, soil nitrous oxide and fuel use in Australian crop production may be much lower than other regions of the world, corresponding to lower feed related GHG emissions. Conversely, electricity related emissions are high in Australia because of the reliance on coal fired electricity generation, which will therefore result in higher impacts from energy intensive stages in the supply chain, such as housing and meat processing in Australia. This study aimed to determine GHG, fresh water consumption, fossil energy demand and land occupation to provide a benchmark for Australian conventional and free range production, and determine impact hotspots in the supply chain, by applying methods and inventories representative of Australian production and processing. The study included two major, contrasting production regions and collected data from multiple companies, to provide results that are broadly representative of Australian chicken meat production.

2. Materials and methods

The study utilised primary and secondary data sources and methods reflecting Australian production systems where available. Specific data collection and modelling approaches are outlined in the following sections.

2.1. Impacts assessed

The study assessed GHG emissions using the IPCC AR4 global warming potentials of 25 for CH_4 and 298 for N_2O, as applied in the Australian National Inventory Report (NIR) (Commonwealth of Australia, 2015b). GHG emissions associated with land use (LU) and direct land use change (dLUC) were included and reported separately, following guidance from the Livestock Environmental Assessment and Performance partnership (LEAP, 2014). Fossil fuel energy demand was assessed by aggregating all fossil fuel energy inputs throughout the system and reporting these per mega joule (MJ) of energy, using lower heating values (LHV). Fresh water consumption (L) was assessed using methods consistent with ISO (2014), as described in the following sections. One exception was the assessment of fresh water consumption associated with land use change (LUC) which was not assessed because of the lack of suitable inventory data for the background grain processes. The impact on water use was assessed using the stress-weighted water indicator, based on Pfister et al. (2009). The value was expressed as a water equivalent (H2O-e; Ridoutt and Pfister, 2010), by dividing the stress weighted water value by the global average water stress volume. Land occupation was assessed by aggregating impacts throughout the supply chain, and both total land occupation and arable land occupation are reported in square meter years (m^2 yr). All modelling was carried out using SimaPro™ 8.0 (Pré-Consultants, 2014) and the study applied an attributional modelling approach.

Production from two Australian states (Queensland – QLD and South Australia – SA) and two production systems: conventional housing (indoor housing with tunnel ventilation), and free range (FR) production were investigated. Queensland is located in the mid-north eastern part of Australia, while SA is located in the southern-central part of the continent. Each production region mainly utilised feed produced in the region, though the QLD supply chain utilised slightly more imported feed ingredients. The primary production supply chain included breeding (rearing of parent birds, fertile egg production and hatchery processes), grow-out and meat processing, with all associated inputs. Grandparent and great grandparent breeding systems were not included since they were found to contribute <1% of impacts, in a preliminary scoping analysis conducted as part of the study (unpublished data). Data were collected as part of the study to cover a 12 month production period (2009–2010), from three major vertically integrated poultry producers across 38 facilities. The FR supply chain consisted of one company supply chain in each state, each with multiple FR farms. These were combined to ensure company data were confidential, and to provide a larger and more representative FR dataset. However, a limitation to this was that we could not compare conventional with FR production within each state supply chain. Data collection processes are described in the following sections. The end-point of the supply chain was the cold storage unit where chicken meat is stored prior to wholesale distribution. Results are presented using two functional units (FU): 1 kg of chilled chicken (whole bird) ready for packaging and distribution to retail, and 1 kg of boneless, skinless chicken portions, ready for packaging and distribution to retail. The system boundary of the study is shown in Fig. 1.

2.2. Life cycle inventory

The inventory was separated and reported separately for each stage of the supply chain. Data collection methods and calculation methods are described in the following sections.

2.2.1. Feed use and milling

Feed use for breeding birds and meat chickens was reported by each company, in each state. Birds are phase fed, and diets may change during the year in response to changes in the availability of commodities. Each company operated their own feed mill, and commodity inputs, energy and water use, and transport distances were reported by each feed mill over a 12 month period (Table 1). The aggregated rations are shown in Table 2.

2.2.2. Feed production

Major feed grains were modelled for Australian grain processes by the authors, or using processes available from the AustLCI

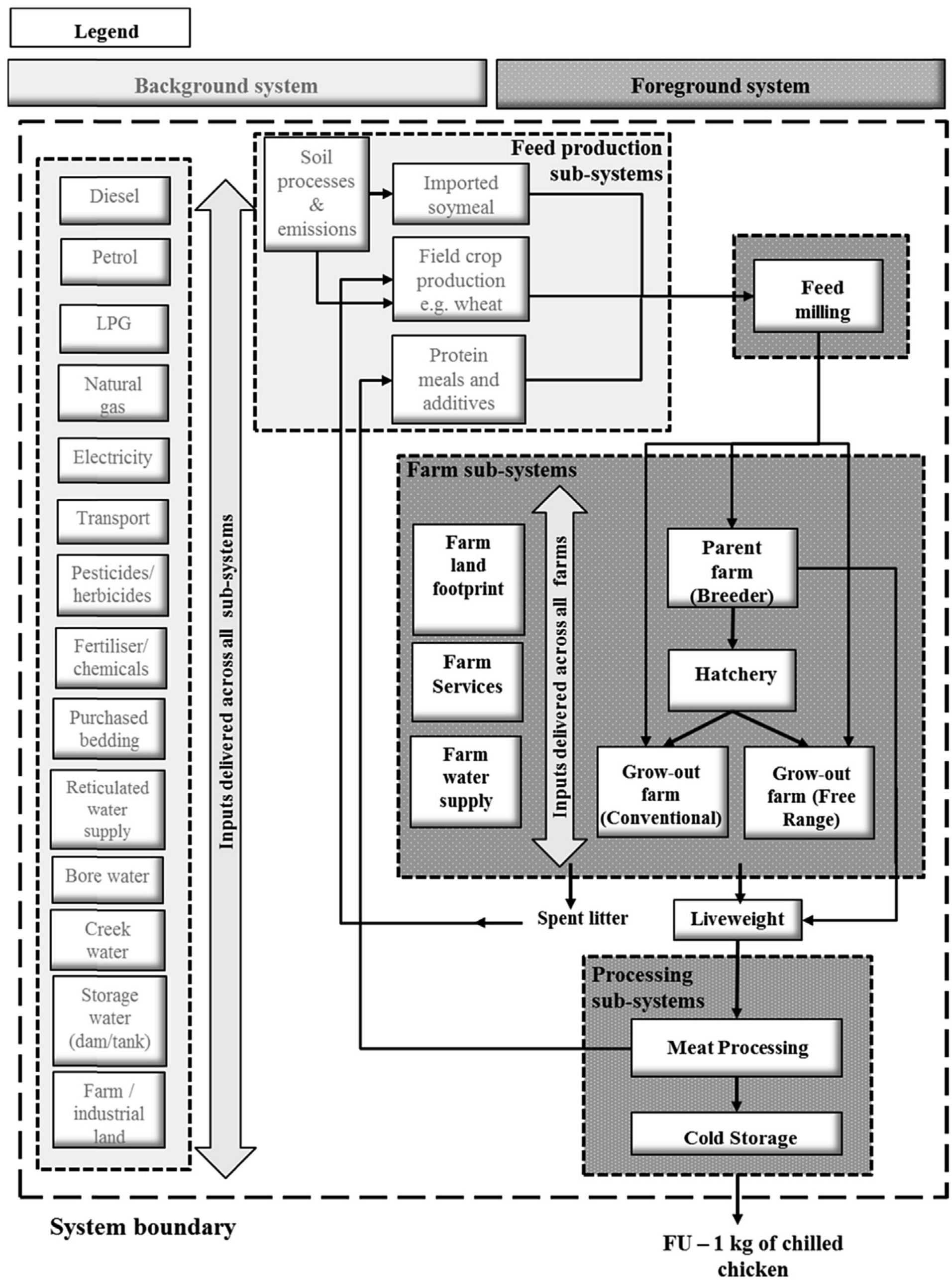

Fig. 1. Chicken meat production system boundary.
FU: functional unit.

Table 1
Average feed milling inputs per tonne of ration produced for Queensland and South Australian supply chains.

Inputs	Queensland	South Australia
Electricity (kWh/tonne[a])	25.4	18.8
LPG (MJ/tonne[b])	56.4	0.2
Natural gas (MJ/tonne)	0.0	69.0
Fresh water consumption (L/tonne)	72.0	89.4
Transport (t.km[c]/tonne)	286.1	105.4

[a] Kilo watt hours, reported per tonne, “as-fed” (inclusive of moisture).
[b] Mega joule.
[c] Tonne kilometres.

database (Life Cycle Strategies, 2015) where available. All processes used emission factors from the Australian NIR 2013 (Commonwealth of Australia, 2015b). For major grains in each region, the proportion of grain produced in different systems (i.e. dry land and irrigated) was determined using the proportion of crop land irrigated and average irrigation rates in each state over three years reported by the ABS (ABS, 2009, 2010, 2011). Losses associated with the supply of irrigation water were 27.1%, based on the national water accounts (ABS, 2012). Grain processes were aggregated to provide an average market for the major grains in each state. LU and dLUC emissions were not included in the Australian grain inventory datasets available, and were therefore assessed separately. Annualised emissions associated with conversion of forest land to crop land were 4,755,000 t CO_2-e in the period 1990–2010 (Commonwealth of Australia, 2015a). The analysis of LU emissions from crop land were −4,800,000 t CO_2-e (negative emissions indicate carbon sequestration), annualised

Table 2
Commodity inputs per tonne of ration for the Queensland, South Australian and free range supply chains.

Commodities (protein %)	Queensland (kg/tonne)	South Australia (kg/tonne)	Free range (kg/tonne)
Sorghum (10%)	434.0	0.0	219.0
Wheat (13%)	204.2	538.8	379.9
Barley (11%)	0.0	139.0	0.0
Soybean meal (45%)	188.6	163.2	47.4
Field pea (23%)	0.0	42.2	125.9
Faba bean (26%)	19.1	0.0	0.0
Canola meal (36%)	40.8	35.6	123.8
Animal by-product meals (50%)	57.3	33.0	70.9
Oil/tallow	26.3	18.7	14.5
Feed additives	29.7	29.5	18.6
Total	1000.0	1000.0	1000.0

over the same period. Carbon sequestration in Australian crop land is mostly in response to carbon sequestration resulting from adoption of improved cropping practices over the past 20 years. When divided by the average total land area sown to crops annually in Australia over the period 1990–2010, annualised emissions from LU and dLUC were −229 and 227 kg CO_2-e/ha. Differences in LU emissions or sequestration may exist between cropping regions in Australia based on specific management. However, as suitable disaggregated datasets were not available to assess impacts associated with individual crops, or cropping regions by state, in the present study we accounted LU and dLUC emissions from Australian crop land at the national scale.

Where data were unavailable for some small dietary inputs, such as vitamins, substitutions were made with other feed inputs using product cost to guide the substitution. Imported soybean meal was modelled using data from the EcoInvent database (Swiss Centre for Life Cycle Inventories, 2014), based on the relative imports of soybean meal from the major sources of Australian imports; South America (80%) and the United States of America (USA) (20%) (OEC, 2015). Irrigation water associated with imported soybean meal from USA was assumed to be 263 m^3 water/tonne soybeans after Aldaya et al. (2010), and irrigation water use in South America was assumed to be 877 m^3/tonne irrigated soybeans (Arena et al., 2011), with irrigated soy representing 3% of the total crop.

2.2.3. Breeding and hatching

Inputs associated with breeding and hatching were collected from five company's breeder farms and hatcheries across the two states. Water data were collected from farm records of the total volume of water pumped. Water was predominantly used for drinking and cleaning. Drinking water, after ingestion, was respired, excreted with manure or integrated into the bird. Each of these flows ultimately resulted in water consumption or removal from the original water catchment in the product. Thus, all drinking water was treated as fresh water consumption. Likewise, cleaning water was considered a consumptive use as small volumes were used and sheds were left to dry out after cleaning, resulting in evaporation of the water used. Where water was supplied from a system that incorporated open water storages, evaporative losses were assessed and included in the total volume of fresh water consumption used. Major inputs are shown in Table 3. In addition to inputs, the mass of live weight in spent hens for meat processing was 32.2 and 22.0 kg for QLD and SA respectively.

Table 3
Major inputs associated with breeding and hatching, reported per 1000 day-old chicks produced.

	Queensland	South Australia	Free range
Feed Ration, kg as fed	403.1	423.1	448.0
Electricity, kwh	173.1	144.2	82.9
LPG, L	9.1	7.8	19.8
Diesel, L	11.5	0.4	0.9
Petrol, L	0.8	0.4	1.2
Fresh water consumption, L	1850.0	2120.0	5014.0

2.2.4. Breeding farm manure management

Manure GHG emissions (CH_4, N_2O) and indirect emission precursors (NH_3) were estimated by predicting nitrogen (N) and volatile solids (VS) excretion using mass balance principles, and applying emission factors from the Commonwealth of Australia (2015b). Excreted N was determined from the difference between N inputs (in feed) and N outputs (in bird mass, mortalities and eggs). Excreted VS was determined by subtracting manure ash excreted from total solids (TS), which represented the residual of non-digested feed (Dong et al., 2006). The sensitivity of the model to manure emission factors was tested by performing a comparison with the IPCC factors (Dong et al., 2006). Manure was typically removed from the site and sold for a small amount of money, and was treated as a residual, with no allocation process applied (LEAP, 2015). Indirect nitrous oxide was modelled from ammonia volatilisation. All animal houses were constructed with impervious floors and therefore nitrate leaching and runoff were assumed to be negligible. Factors are shown in Table 4.

2.2.5. Meat chicken grow-out phase

Flock performance, including feed intake, growth rate, mortality rate and the total mass of birds harvested were determined from records supplied by each company in each state and represent actual performance under commercial conditions (Table 5). The grow-out phase is generally contracted out to third party growers in Australia, and these growers are responsible for animal husbandry, housing and litter management. Records of water use, energy use, cleaning and litter management were collected from 22 farms across the two states, covering a 12 month period. Volumes of drinking, cooling and cleaning water were collected from farm records. Drinking and cleaning water were handled in the way described for the breeding flocks, whereas cooling water was used in evaporative cooling systems and was therefore a consumptive use. In some cases, on-site water storages were used and evaporation from these storages was included in the total volume of fresh water consumption used. Material inputs are shown in Table 6.

2.2.6. Grow-out phase manure management

Manure excretion and manure emissions were determined using the same mass balance approach described for the breeder facilities. Emission factors for birds housed on litter were from the Commonwealth of Australia (2015b) and recent Australian research (Wiedemann et al., 2016b), with the latter given

Table 4
Manure greenhouse gas emission factors for meat chicken houses.

Emission source	Factor applied	Comparison factor – IPCC
Manure methane, Methane Conversion Factor (MCF)	0.007[a]	0.015[c]
Manure nitrous oxide, kg N_2O-N/kg N excreted	0.0035[a]	0.001[c]
Manure nitrous oxide (FR area), kg N_2O-N/kg N excreted	0.02[d]	0.02[d]
Manure ammonia, kg NH_3-N/kg N excreted	0.11[a]	0.4[c]
Indirect nitrous oxide, kg N_2O-N/kg NH_3N	0.002[b]	0.01[d]

[a] Wiedemann et al. (2016b).
[b] Commonwealth of Australia (2015b).
[c] Dong et al. (2006).
[d] De Klein et al. (2006).

Table 5
Performance data for meat chickens in the grow-out phase.

Production data	Queensland	South Australia	Free range
Total bird production, per year	949,662	1,955,162	590,191
Final bird weight, kg	2.5	2.8	2.4
Final bird age, days	42.8	42.2	41.6
Flocks, per year	5.5	5.9	6.5
Feed conversion ratio, kg feed/kg live weight	1.89	1.85	1.89

Table 6
Grow-out phase inputs reported per 1000 kg of live weight produced.

Materials	Queensland	South Australia	Free range
Feed ration, kg as-fed	1886.0	1853.0	1886.0
Day-old chicks	423.4	402.5	448.0
Electricity, kWh	99.8	96.2	82.9
LPG, L	13.2	26.5	19.8
Natural gas, m^3	25.7	n.a	n.a
Diesel, L	0.4	1.6	0.9
Petrol, L	0.6	0.5	1.2
Staff transport, km	9.6	3.7	3.7
Fresh water consumption – animal houses, L	3206.0	5890.0	5014.0
Fresh water consumption – water supply system losses, L	83.2	n.a	n.a
Bedding – shavings/straw, kg	127.0	162.0	240.5
Pesticides, L	0.1	0.1	0.1
Disinfectant, L	0.8	0.5	0.7

preference where data were available. Factors are shown in Table 4. The sensitivity of the model to manure emission factors was tested by performing a comparison with the IPCC factors (Dong et al., 2006). Manure was removed from the meat chicken houses at the end of each production batch, and sold to local farmers as a fertiliser. Manure sales represented a very small fraction of the total value of production. As a result, they were treated as a residual flow with no allocation of impacts from the production system to the manure product. Impacts from manure following removal from the chicken house were assumed to be attributed to the system using the manure as a fertiliser.

2.2.7. Meat processing

Meat processing data were averaged from data collected at three processing plants in QLD and two processing plants in SA. All meat processing plants used water from reticulated supplies, with some facilities supplementing this with on-site groundwater extraction. All but one processing plant released effluent water into the city sewerage treatment system, where it was treated and returned to the same water catchment. One QLD processing plant irrigated water to pasture on-site, which was considered a consumptive use attributable to the meat processing system. The processing plants reported resource use relative to carcase mass, but all plants produced a combination of chicken products, including (carcase weight) CW and both bone-in and boneless portions. Major inputs associated with processing are reported in Table 7.

2.3. Handling Co-production

Total product mass from the system was inclusive of meat chickens, small amounts of meat from end-of-life breeding hens, and edible offal. Co-products included manure, pet food and processing by-products for rendering. Manure was a very low value output from the system and was treated as a residual. Emissions associated with transport, storage and land application of manure were attributed to the systems utilising the manure, which included grain production systems producing grain for the chicken meat system. Some 19% of litter is used for grain production in Australia (Dorahy and Dorahy, 2008), and total N supply from poultry litter contributed 1% of total crop N requirements.

Meat processing by-products (i.e. renderable products, pet

Table 7
Meat processing inputs, reported per 1000 kg carcase weight processed.

Inputs	Queensland	South Australia
Electricity, kWh	239.3	155.0
LPG, L	3.1	7.7
Natural gas, m^3	6.6	6.6
Diesel, L	2.5	0.2
Petrol, L	0.3	0.0
Total water supply, L	5804.5	6846.7
Fresh water consumption, L	2472.1	1505.8
Cleaning chemicals, L	7.3	3.4

foods) were handled using economic allocation. The economic value of CW represented 98.5–99.2% of the output from meat processing, with the renderable and pet food products contributing the remaining revenue. Impacts reported per kilogram of chicken portions were determined using yield factors and mass flows described in Wiedemann and Yan (2014).

3. Results

Fossil fuel energy demand was 18.1 and 21.4 MJ/kg CW for the SA and QLD conventional systems respectively, and 18.3 MJ/kg CW from FR production. Feed production contributed 53–59% of fossil fuel energy demand, with most energy in the feed production system being related to field operations and energy associated with fertiliser manufacture. Meat processing (13–16%) and housing (18–21%) were also substantial contributors to fossil fuel energy demand.

Fresh water consumption ranged from 38 to 111 L/kg CW for the SA and QLD conventional production systems, and 70 L/kg CW from FR production. Water associated with the production of feed contributed 69–86% of fresh water consumption, predominantly from irrigation of grain. The grow-out phase used 5–21% of total water, mainly for drinking and cooling, while meat processing and breeding contributed smaller amounts.

Stress weighted water use was 26 and 36 L H_2O-e/kg CW in the QLD and SA conventional supply chains respectively, and 21 L H_2O-e/kg CW in the FR supply chain. Stress weighted water use was primarily associated with irrigation water use, though the contribution from the grow-out and processing stages of the supply chain tended to be higher than observed for fresh water consumption, because these operations tended to occur in more water stressed catchments. Notably, stress weighted water use was higher in the SA supply chain, despite fresh water consumption being lower, because water stress was higher in parts of this supply chain.

Arable land occupation ranged from 14.0 to 22.5 m^2/kg CW for the QLD and SA conventional production systems, and 18.2 m^2/kg CW for FR production. Total land occupation was 1–2% higher than arable land occupation, when the small amount of land used for bird housing, processing and other background processes were included.

Greenhouse gas emissions (excl. LU and dLUC) were 2.2 and 1.8 kg CO_2-e/kg CW for QLD and SA conventional production respectively. Emissions from FR production were 1.8 kg CO_2-e/kg (Fig. 2). Emissions from LU and dLUC were 1.2 kg CO_2-e for QLD and 1.0 kg CO_2-e/kg CW for the SA conventional systems. Impacts from FR production were 0.4 kg CO_2-e/kg CW. LU and dLUC emissions arose from soymeal production, which was included at a higher rate in the conventional diets compared to the FR. Feed production represented the largest contributing stage of the supply chain for GHG emissions, with impacts ranging from 55 to 60%, and 64–75%, if LU and dLUC were included. Emissions from the grow-out phase were 12–16%, with the majority of this being associated with energy use for housing and a smaller proportion contributed from manure emissions. Meat processing contributed 12–18%, with the main differences relating to energy use and emissions arising from waste water treatment, which were lower in the SA supply chain.

Impacts per kilogram of chicken portions are shown in Table 8. Results were 39% higher than for chilled, whole birds because of the loss of mass associated with the boneless product and the additional impacts associated with further processing.

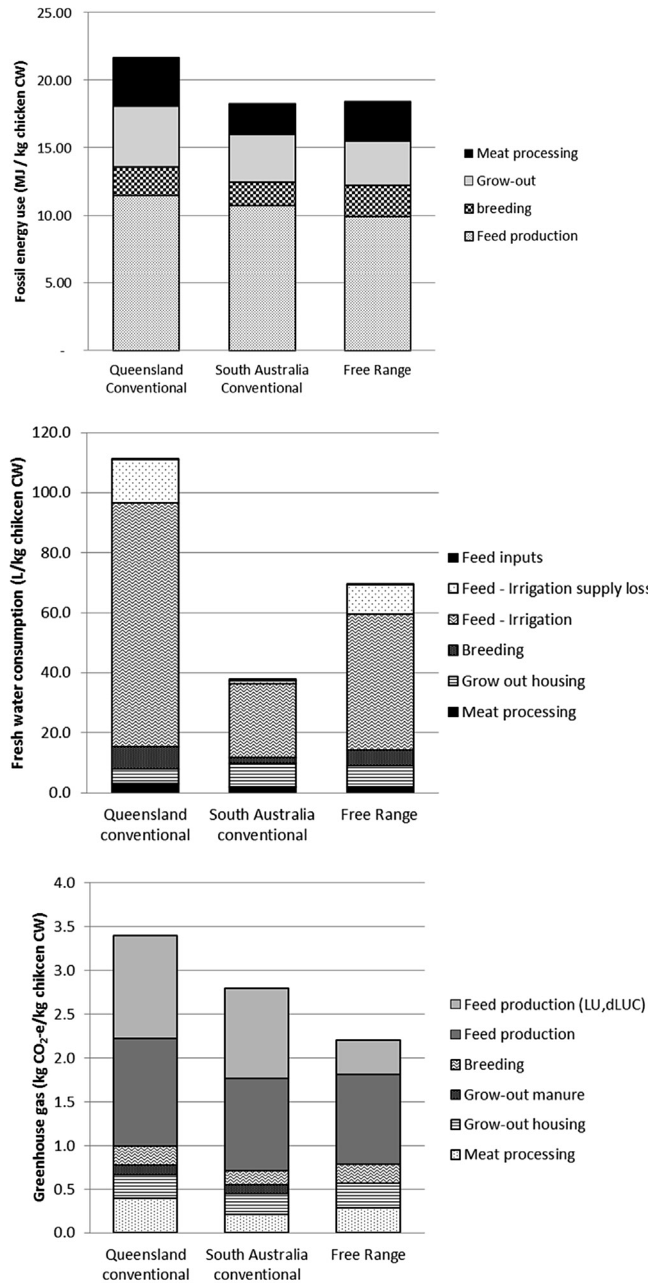

Fig. 2. Three graphs showing fossil energy, fresh water consumption and greenhouse gas emissions from chicken meat (Carcase weight – CW) produced in Queensland and South Australian conventional systems and free range production. LU, dLUC: Land use and direct land use change greenhouse gas emissions.

4. Discussion

This study provides a new benchmark assessment of Australian chicken meat production through to production of a wholesale product, with novel results related to water, water stress and arable land occupation. The GHG assessment includes revised methods supported by recent research in manure management and crop fertiliser emissions, and included assessment of LU and dLUC emissions. We did not include nutrient related impacts such as eutrophication, and did not investigate land degradation impacts, and these areas require further research to produce a broader assessment of environmental impacts from the supply chain.

4.1. Sensitivity to model assumptions

Across all impact categories, feed use was the greatest source of

Table 8
Resource use and environmental impacts from meat chicken production in three supply chains, results reported per kg of boneless chicken portions.

	Fossil fuel energy demand, MJ	Fresh water consumption, L	Stress weighted water, L H_2O-e	Arable land, m^2	Greenhouse gases, excl. LU[a] and dLUC[b], kg CO_2-e	Greenhouse gases, LU an dLUC, kg CO_2-e
Queensland conventional	29.8	154.7	36.4	19.5	3.1	1.68
South Australia conventional	25.1	52.7	50.7	31.3	2.5	1.40
Free range	25.5	96.8	29.0	25.3	2.5	0.56

[a] Land use.
[b] Direct land use change.

impacts, and the model was therefore sensitive to a number of feed related assumptions. Impacts were greatest from the three largest commodities, wheat, sorghum (QLD) and soybean meal. The relatively low emission profile of Australian cereal grains was the major factor explaining low emissions from chicken meat in the present study. We compared grain inventory processes applied in the present study (derived from the AustLCI—Life Cycle Strategies, 2015) with other Australian studies (Brock et al., 2012) and found few differences in GHG emissions, provided emission factors were harmonised. This suggests a reasonable level of agreement between grain LCI data for major Australian processes. We found that the relative proportion of different cereals (wheat, barley and sorghum) also had little effect on the impacts generated by the diet. This was provided the overall proportion of cereals was the same, because the impacts associated with the different cereal grain productions systems was similar. However, differences in the inclusion rate of soybean meal resulted in substantial differences in dLUC emissions, fossil fuel energy demand, fresh water consumption and stress weighted water use. Where diets were formulated to utilise Australian field pea as the major protein grain, impacts were found to be 15% lower for GHG and energy, 90% lower for fresh water consumption, 90% lower for stress weighted water use and 94% lower for LU and dLUC emissions. This dietary change was more extreme than those modelled by Leinonen et al. (2013) and the change in LU and dLUC emissions was consequently much greater. In practice, smaller reductions in soymeal inclusion are more likely. The diets modelled in the present study were representative of the vast majority of chicken meat production in each state over the 12 month period assessed. However, inter-annual variation in commodity inclusion rates may occur and these results may only be taken as representative of diets with similar inclusion rates of soymeal.

Fresh water consumption and stress weighted water use were also sensitive to assumptions regarding irrigation rate and irrigation region. From year to year, water supply fluctuates substantially and consequently irrigation rates and the total area irrigated will vary. In the present study, a three year average irrigation rate was applied and the total irrigation volume was divided by total crop yield in each state, to determine the weighted average volume of irrigation water per tonne of grain produced. The dataset did not allow irrigation water flows to be attributed to specific cereals or end markets (human consumption vs animal consumption), and this remains a knowledge gap to be addressed by future research. To explore the sensitivity of the model to inter-annual variation in irrigation rate, we compared irrigation rates from a low water availability year (2010) and a high water availability year (2008). For the state with the largest volume of irrigation use (QLD), water was found to vary between 83 and 157 L/kg CW between the two years. Inter-year variation in stress weighted water use is expected to be very high in response to the different rates of irrigation used and the variable rates of extraction (and therefore water stress) from year to year. In the present study, static, course resolution water stress values were used and as a consequence, stress weighted water use results should be viewed with a degree of caution. These results could be improved through development and application of annual WSI values for Australian catchments.

Greenhouse gas emission results per kilogram of chicken were found to be ~4% higher when IPCC (Dong et al., 2006) emission factors were applied, suggesting the model was not sensitive to the application of emissions from Australian research. To test the sensitivity of the results to electricity use, these inputs were varied by 15% (difference between the highest and lowest company average) which resulted in <1% impact on total fossil energy. Differences in electricity use during meat processing resulted in more significant changes in total fossil energy, with more efficient plants having 5% lower total energy per kilogram of chicken than less efficient plants.

4.2. Main impact sources and mitigation

Australian meat chicken production is dominated by large, vertically integrated producers that manage the genetics, nutrition and processing of the birds, resulting in benefits from economies of scale and high degrees of efficiency at critical points in the supply chain. The Australian industry is focused primarily on domestic production rather than export, and has grown at an annual rate of ~2.5% each year for the past 10 years (ABS, 2014), in response to increased consumer demand for product. However, as the chicken meat industry continues to expand, the impact on finite resources and impacts from production will also increase. As a result, production efficiency throughout the supply chain remains a priority, particularly in the areas of greatest impact.

While the industry has no direct control over grain production, it represents the major impact area for arable land and water resources, and the scarcity of these resources will be relayed to chicken meat through grain supply. While some opportunities may exist to change the type of grains used by the industry to reduce impacts, the long term efficiency will be more heavily influenced by changes in feed conversion ratio (FCR). According to McKay et al. (2000), the annual rate of improvement in FCR is 0.02, resulting in a 0.6 kg reduction in feed requirements over the previous 30 years. In the present study, a 0.1 improvement in FCR resulted in a 3–4.5% decrease in GHG (inc. LU and dLUC) depending on the diet. Improved FCR has a positive effect on both upstream impacts from feed production, and downstream impacts from manure emissions, as manure production decreases with improved FCR. Wiedemann et al. (2016b) demonstrated that reduced dietary crude protein, achieved by improving the balance of amino acids in the diet to ensure the nutritional requirements of the bird was optimised, could reduce both FCR and manure emissions. This could result in lower impacts from two major impact hotspots in the supply chain. For those supply chains with water intensive diets (QLD), improved feed conversion ratio also reduced fresh water consumption by as much as 5% for each 0.1 change in FCR. Similarly, improved FCR reduced arable land requirements, particularly in SA where yields are lower and land requirements are consequently higher. Such improvements are vital for the ongoing sustainability of the industry, to minimise the pressure on finite water and arable land resources.

After feed use, the grow-out phase and meat processing contributed the largest proportion of GHG, energy and fresh water consumption in the supply chain. The substantial contribution from the grow-out phase to GHG and energy demand has prompted further research into energy efficiency from the grow-out stage (McGahan et al., 2012), and the companies participating in the study have implemented energy and water saving activities in the meat processing plants to reduce impacts over time. Modest opportunities exist to mitigate manure GHG, though these strategies are not expected to have a substantial impact on the GHG emissions from full supply chain. Further research into energy production from manure/litter may provide greater opportunities to reduce emissions and lower energy demand from production, and further analysis is warranted in this area.

4.3. Regional differences

Between the different regions assessed, production in SA tended to be more energy efficient, with lower GHG emissions and lower fresh water consumption. This result was due, in part, to lower supply chain fossil fuel energy demand in SA, and mainly because the diets used in SA had ~20% lower GHG and energy impacts and 63% lower fresh water consumption than the QLD diets. In contrast to this, arable land occupation was higher, as a result of the lower intensity grain production systems and lower yields in this region compared with the major grain production regions in QLD and northern New South Wales (NSW). Stress weighted water use was also higher, because the SA supply chain was more reliant on highly stressed catchments. As a result, the impact of water use in SA was greater than QLD despite the lower volume of water used. Considering the importance of location in assessing impacts from feed production, an analysis of production in the major state of NSW was done for comparison. Impacts from this supply chain were comparable to the QLD supply chain for all impacts except water stress, which was 98 L H_2O-e/kg CW in response to highly stressed irrigation water use in southern NSW. Considering this finding, we expect that the national average fresh water consumption to be closer to the QLD value than SA, and water stress to be higher than observed in either state studied here. Similarly, national water use estimates for Australian beef were higher than regional estimates (Wiedemann et al. 2015a). These results, while quite specific to Australia, suggest that water may be a much more variable input between states, and possibly countries, than GHG. Accurate benchmarking would require consistent, accurate, spatially and temporally specific feed grain datasets to produce robust results.

4.4. Benchmarking

Comparison of LCA studies is complicated by the application of different assessment methods, system boundaries and assumptions. Per kilogram of live weight, GHG emissions excluding LU and dLUC in the present study ranged from 1.1 to 1.3 kg CO_2-e, which was similar to production in the USA (Pelletier, 2008), but lower than previously reported by Bengtsson and Seddon (2013) for Australian chicken meat production. With LU and dLUC emissions included, results were 2.2 and 1.9 kg CO_2-e/kg live weight (LW) for the conventional production and 1.6 kg CO_2-e/kg LW for FR, which was lower than Leinonen et al. (2012) who reported values of ~3.1–3.6 kg CO_2-e when values were converted to a LW basis. The main factors contributing to lower emissions in the present study relate to feed sources and to some extent, manure emissions. GHG emissions associated with rations in the present study ranged from 0.39 to 0.48 kg CO_2-e/kg feed, or 0.53–0.92 kg CO_2-e/kg ration with LU and dLUC emissions included. By comparison, Leinonen et al. (2012) reported impacts of 1.1 and 1.0 kg CO_2-e for their standard and FR rations respectively, and impacts were 1.5 kg CO_2-e/kg feed in MacLeod et al. (2013). The lower impacts associated with Australian feed production are well understood. Australian emission factors for crop fertiliser application (Commonwealth of Australia, 2015b) are 80% lower than international defaults reported by De Klein et al. (2006), because of the low soil moisture conditions experienced in Australia. While yields are also low, energy related inputs relative to grain production are low compared to northern Hemisphere grain production. As a consequence, impacts for major Australian grains such as wheat are in the order of 0.2 kg CO_2-e/kg grain (i.e. Brock et al., 2012) and these values are lower still with more recent fertiliser emission factors applied (Commonwealth of Australia, 2015b). Field emissions associated with manure application to crops, which were substantial in MacLeod et al. (2013), were found to be minor in Australia, where manure is a small source of crop fertiliser N. The present study also provided updated emissions from manure which were substantially lower than previously reported by Bengtsson and Seddon (2013) for Australian chicken meat, as this study used superseded inventory emission factors.

Fossil fuel energy demand in the present study was 11.5–13.1 MJ/kg LW for the conventional production systems, which was lower than the 18 MJ reported by Leinonen et al. (2012), but similar to the 14.9 MJ/kg LW reported by Pelletier (2008) for broiler production in the USA. No studies were found that reported water use using a comprehensive assessment of fresh water consumption. Never-the-less, results were of a similar magnitude to the fresh water depletion reported by Bengtsson and Seddon (2013), and much higher than the 3–5 L/kg LW of direct water use (inventory value) reported by Leinonen et al. (2012), though this study does not appear to have considered fresh water consumption associated with feed production. Fresh water consumption and stress weighted water may be higher in Australia compared to northern Hemisphere countries, because of the requirements for cooling in chicken meat houses, and irrigation of crops. Land occupation was also substantially higher than reported by Leinonen et al. (2012), in response to the much lower yields from Australian crop production.

In the present study, we found FR production to perform similarly to conventional production with respect to GHG emissions and fossil energy demand, which is contrary to results of Leinonen et al. (2012) and Williams et al. (2006), who found FR to have higher emissions. The similar results between conventional and FR production in the present study were not surprising, considering the similar level of feed conversion efficiency and housing impacts in the two systems. In contrast to the GHG and energy results, water and arable land results for the FR production system were intermediate between the QLD and SA results, primarily in response to the diet composition of the particular FR systems modelled. As the FR farms were located in both states, the proportion of QLD and SA ration components was approximately equal, leading to intermediate impacts for water and arable land; factors that varied strongly between the two states.

This study is the first LCA of Australian chicken meat applying comparable methods to comparison studies for other major Australian livestock products; beef, lamb and pork. When compared per kilogram of boneless product, the study revealed much lower GHG emissions for chicken meat than beef or lamb (Wiedemann et al., 2015b) and around half the emissions of Australian pork (Wiedemann et al., 2016a). However, energy demand was similar to the 27 MJ per kg for grass-fed beef and 24 MJ per kg of lamb, when both were reported at the processor gate. Arable land occupation was also much higher than the 3.2 m^2 reported for grass-fed beef, and 2.5 m^2 reported for lamb. Unsurprisingly, total land occupation was much higher for beef and lamb compared to chicken meat, because of the large areas of non-arable rangelands used for grazing, though the total area of rangelands in Australia is less constrained than the area of arable land. Fresh water consumption was considerably lower for chicken meat compared to beef, though stress weighted water use showed less of a difference between the two. However, because of the regional specificity of stress weighted water assessment, a national average would be required to understand impacts of one industry relative to another with respect to water use.

5. Conclusions

Consistent benchmarking of impacts from meat production systems is hampered by differences in system boundaries, changes in research methods and variation in datasets. This study provides new findings for Australian chicken meat using improved methods, inventories and assumptions to benchmark key resources and environmental impacts. This study presents one of the first comprehensive assessments of water consumption and water impacts associated with chicken meat production. Fresh water consumption (38–111 L/kg CW) was found to be substantially higher than stress weighted water use (21–36 L H_2O-e/kg CW), highlighting the importance of water impact assessment. Water consumption was much more variable between the different production states than GHG, and water consumption also varied substantially from year to year, as a result of changes in irrigation water availability. As a consequence, spatially and temporally specific datasets are required for accurate benchmarking of these resources in Australia. Further studies incorporating fresh water and stress weighted water use in other regions of the world are required to expand the knowledge base regarding water use in meat chicken production. The study found that total GHG impacts were low, ranging from 2.2 to 3.4 kg CO_2-e/kg CW, including LU and dLUC emissions, though inclusion of meat processing increased these emissions by up to 8% compared to the more common farm-gate analyses. Considering feed production and use was the major impact source for all categories studied, improved FCR will result in lower impacts, provided changes don't occur to the diets, or feed supply chains. Impacts were similar between conventional and free range production, with the observed differences primarily related to difference in diets rather than differences in housing. This study did not include nutrient related impacts such as eutrophication or acidification, and did not investigate impacts on land degradation from cropping. Provided suitable methods and datasets are available, inclusion of these impacts is required to broaden the knowledge base regarding impacts from Australian chicken meat. Considering the variability found between states, expansion of this study to include more regions would provide an improved understanding of total impacts and impact hotspots in Australia. Considering the ongoing improvement in feed conversion ratio and production efficiency, and the development of new methods and knowledge in areas covered by this research, revision is recommended at regular intervals to highlight change over time.

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