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Environmental impacts and resource use from Australian pork production determined using life cycle assessment. 2. Energy, water and land occupation

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Abstract. Utilisation of water, energy and land resources is under pressure globally because of increased demand for food, fibre and fuel production. Australian pork production utilises these resources both directly to grow and process pigs, and indirectly via the consumption of feed and other inputs. With increasing demand and higher costs associated with these resources, supply chain efficiency is a growing priority for the industry. This study aimed to quantify fresh water consumption, stress-weighted water use, fossil fuel energy use and land occupation from six case study supply chains and the national herd using a life cycle assessment approach. Two functional units were used: 1 kg of pork liveweight (LW) at the farm-gate, and 1 kg of wholesale pork (chilled, bone-in). At the farm-gate, fresh water consumption from the case study supply chains ranged from 22.2 to 156.7 L/kg LW, with a national average value of 107.5 L/kg LW. Stress-weighted water use ranged from 6.6 to 167.5 L H_2O-e /kg LW, with a national average value of 103.2 L H_2O-e /kg LW. Fossil fuel energy demand ranged from 12.9 to 17.4 MJ/kg LW, with a national average value of 14.5 MJ/kg LW, and land occupation ranged from 10.9 to 16.1 m^2/kg LW, with a national average value of 16.1 m^2/kg LW and with arable land representing 97% to 99% of total land occupation. National average impacts associated with production of wholesale pork, including impacts from meat processing, were 184 ± 43 L fresh water consumption, 172 ± 53 L H_2O-e stress-weighted water, 27 ± 2.6 MJ fossil fuel energy demand and 25.9 ± 5.5 m^2 land/kg wholesale pork. Across all categories through to the wholesale product, resource use was highest from the production of feed inputs, indicating that improving feed conversion ratio is the most important production metric for reducing the resource use. Housing type and energy generation from manure management also influence resource use requirements and may offer improvement opportunities.

Additional keywords: agricultural systems LCA, water footprint.

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Introduction

Future requirements for food, fibre and fuel production will place increased pressure on the global natural resource base to produce more from less. Globally, meat demand is expected to increase 74% by 2050 because of expanding global population and increased wealth (FAO 2009). However, global arable land and available water resources are constrained (FAO 2009) and fossil fuel resources are finite. In Australia, arable land resources are limited by soil type, climate and vegetation regulations to ~4% of national land mass (Lesslie and Mewett 2013). Water resources in Australia's most heavily populated and water-stressed river basin, the Murray–Darling, are capped, and this restricted supply has led to increased competition between water users (MDBA 2012). For the pork industry, improving resource efficiency is an important strategy for maintaining access to a shrinking pool of resources without dramatically increasing costs. Presently, few data are available to allow the industry to benchmark performance and measure future improvements. Comprehensive assessment methods such as life cycle assessment (LCA) quantify impacts throughout a whole supply chain, including those associated with inputs such as feed. Such tools are effective in comparing different management systems because impacts from the whole system are taken into account, and impacts are reported relative to production. LCA has been applied in Australia to determine supply chain water use, energy use and land occupation using individual farm case studies (i.e. Peters *et al*. 2010; Eady *et al*. 2011; Wiedemann and McGahan 2011), and at the regional or national scale for beef (Wiedemann *et al*. 2015*a*, 2016*b*), export lamb (Ridoutt *et al*. 2012; Wiedemann *et al*. 2015*c*, 2016*d*) and chicken meat (Wiedemann *et al*. 2017). This study provides the first case study and national analysis of water, energy and land associated with Australian pork production using LCA, and is a companion study to the greenhouse gas LCA of Wiedemann *et al*. (2016*a*). The study aimed to benchmark resource use, determine impact hotspots throughout the supply chain, and quantify the reduced impacts from several improvement strategies that may be applied on Australian farms.

Materials and methods

Goal and scope

The study was an attributional investigation of pork production from major production regions and different production systems in Australia, to provide information to the pork industry, research community and the general public.

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. Fresh water consumption was assessed using methods consistent with ISO (2014), described in the following sections. Assessment of stress-weighted water use was based on Pfister *et al*. (2009), and values were divided by the global average water stress index (WSI) (0.602) and expressed as a water equivalent (H_2O-e; Ridoutt and Pfister 2010). Land occupation was assessed by aggregating impacts throughout the supply chain, and both total land occupation and arable land occupation is reported in square meter years (m^2 year).

The primary production supply chain including breeding through to finishing (sometimes at multiple sites) and meat processing was included, with all associated inputs. Data were collected and impacts were assessed from 14 case study farms (CSF), grouped into six supply chains. The supply chains are described by state, piggery size and housing type, as follows: Qld small – medium conventional (Qld SMC), Qld large conventional (Qld LC), NSW conventional housing (breeding pigs) and deep litter housing for grower-finisher pigs (NSW C-DL), Victorian large conventional (Vic. LC), Western Australian large conventional (WA LC) and WA Outdoor housing (breeder pigs) and deep litter housing for grower-finisher pigs (WA O-DL). A national assessment was performed using national survey statistics for the year 2010. Descriptions of data collection methods are provided in Wiedemann *et al*. (2016*a*) and herd performance data are reproduced in Table 1. The end-point of the supply chain was the cold storage unit where pork is stored before wholesale distribution. Results are presented using two functional units (FU): 1 kg of pork liveweight (LW) at the farm-gate, and 1 kg of chilled, bone-in wholesale pork cuts. The system boundary of the study is shown in Fig. 1 with the dashed line denoting the foreground system. The red arrow represents the flow of gilts (young females) and boars back into the breeding herd.

Operation inputs

Operation inputs covering a 12-month production period, including farm water and energy consumption, and purchased services, were accounted and reported per 100 kg LW sold (Table 2). Purchased services (e.g. administration, veterinary services, vehicle repairs) were modelled based on expenditure, using economic input-output data (Rebitzer *et al*. 2002). Impacts associated with transport were assessed by recording all movements of inputs and outputs throughout each stage in the supply chain. Capital infrastructure (i.e. buildings) and machinery were excluded based on their minor contribution (<1% of impacts) assessed during the scoping phase. Land occupation at each piggery was determined using satellite imagery, and included the piggery sheds, roads, effluent and manure treatment areas and where relevant, effluent disposal areas. Purchased inputs for the national herd were determined from an inventory of 33 piggeries (FSA Consulting, unpubl. data) and the CSF inventory dataset. Table 2 shows the operation inputs for the CSF and the national herd.

Impacts generated off-farm via the use of purchased inputs were modelled using background data sourced from the Australian life cycle inventory database (Life Cycle Strategies 2015) where available or the European EcoInvent (3.1) database (Weidema *et al*. 2015). Transport data were modelled using the methodology detailed in Wiedemann *et al*. (2016*a*).

Feed use, feed production and milling

Feed use at the CSF was determined from records of feed deliveries over a 12-month period. These diets, together with four representative diets for the national herd, are reported in Wiedemann *et al*. (2016*a*). Pig production relied predominantly on locally grown cereal grains, pulses, by-products from other production systems and some imported products such as soy meal, which is sourced predominantly from the USA and South America. Feed additives, such as synthetic amino acids are an important feed contribution. Diets are described in Wiedemann *et al*. (2016*a*) and are reproduced in the Supplementary material. Major feed grains were modelled from Australian grain processes available from the AustLCI database (Life Cycle Strategies 2015) and Wiedemann *et al*. (2010). For the major grains in each region, the proportion of grain produced under dry land or irrigated production was determined using the proportion

Table 1. Case study farm (CSF) herd production databased on primary data from major production regions

FCR, the feed conversion ratio, calculated from kilograms of feed (as fed) divided by total liveweight out (including cull sows). See text for explanation of the CSF (Qld SMC, Qld LC, NSW C-DL, Vic. LC, WA LC and WA O-DL)

Parameter	Qld SMC[A]	Qld LC	NSW C-DL	Vic. LC	WA LC	WA O-DL	National herd (%)
Litters/sow.year	2.1	2.4	2.3	2.3	2.3	2.1	2.3 ± 3.5
Pigs weaned/sow.year	19.1	22.4	20.0	24.7	24.7	16.5	21.4 ± 9.4
No. of sows	318	8229	4680	1950	6370	1956	231 647 ± 4.0
Sow mortality rate (%)	6	9	5	5	10	10	10 ± 1.8
Sow culling rate (%)	33	32	46	36	31	41	37 ± 4.0
Average sale weight of slaughter pigs[B] (kg)	104.1	84.2	99	107	96.7	102.3	97.4 ± 5.1
Average age of slaughter pigs (days)	155.2	136.5	156	154	160.2	176.3	151.4 ± 5.5
FCR (whole herd)	3.2	2.9	2.7	2.4	2.7	3.2	3.1 ± 6.7

[A]Data were averaged independently across the five piggeries.
[B]Weighted average of all pigs sold.

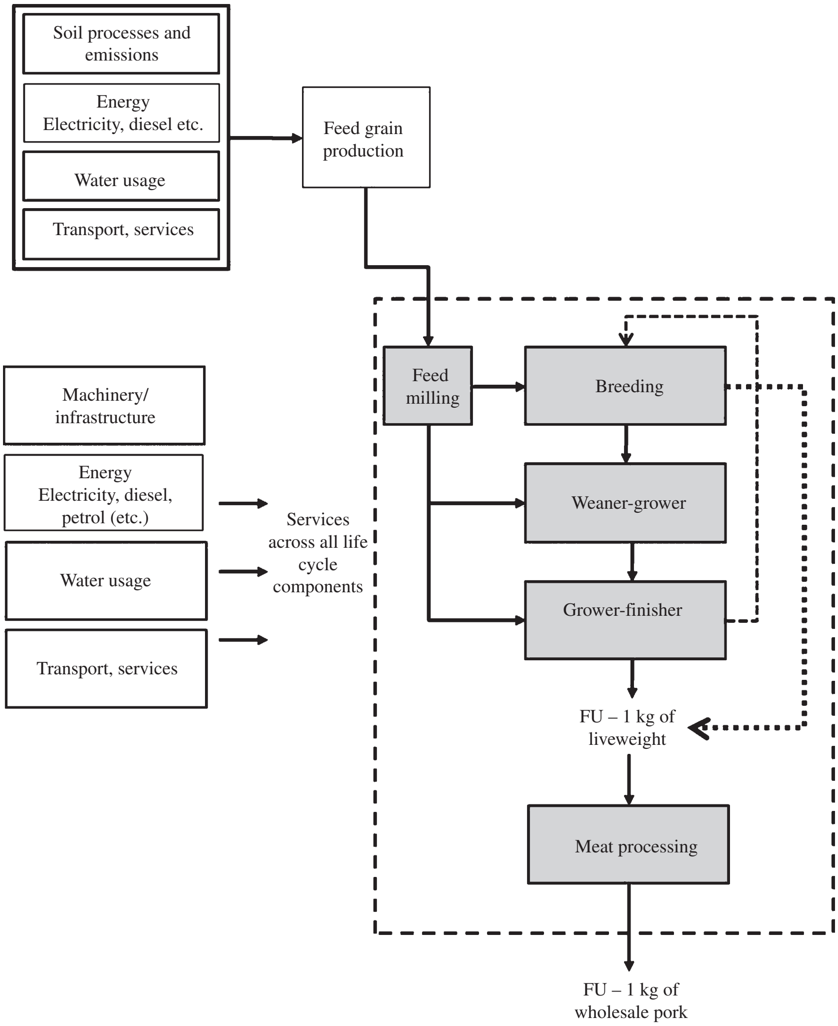


Fig. 1. System boundary with foreground system boundary noted within the dashed lines.

of crop land irrigated in each state (ABS 2009, 2010, 2011). Losses associated with irrigation water supply of 27.1% were applied, based on the ABS national water accounts (ABS 2012). Grain processes were aggregated to provide an average market for the major grains in each state (see Wiedemann *et al.* 2016*a*; Supplementary material). The area of land occupation associated with crop production was a function of crop yield (see Supplementary material), and calculated in each grain inventory process. Crop yields were cross checked against national datasets to ensure representativeness, and further details of the crop inventory are provided in Wiedemann *et al.* (2016*a*).

Feed mill energy and water data were collected from three commercial feed mills. Water use averaged 113 L/tonne of ration produced and energy data were detailed in Wiedemann *et al.* (2016*a*). These data were averaged and used for all CSF and the national herd, with state-based electricity processes used.

Fresh water consumption

Water inputs were measured using water meters at most piggeries. A water balance model was established for each piggery to determine fresh water flows and water consumption throughout the piggery. Additionally, water balances were used to determine flows and losses in the water supply system. Within the piggery, water is used for livestock drinking, cleaning and cooling, and outputs occur via evaporation, respiration, incorporation into product and flows into the manure management system. Drinking water was either incorporated into the product and exported from the catchment (consumptive use) or voided in urine or manure. Manure and urine, together with cleaning water and spilled water in conventional systems, enters the effluent treatment system where water is returned to the atmosphere either by direct evaporation from effluent ponds, or via evapo-transpiration of irrigated effluent on nearby pastures. In sheds using deep litter, the moisture is captured in the litter, and is assumed to evaporate from the litter during storage or during land application. Thus, all water inputs were consumed by the system via multiple pathways and detailed water balance processes for the animal sheds could be simplified by treating all water inputs as consumptive uses, though the pathways were diverse.

Table 2. Aggregated general services and energy inputs for case study farms (CSF) and national herd per 100 kg of finisher liveweight (LW) sold
Values are means. See text for explanation of the CSF (Qld SMC, Qld LC, NSW C-DL, Vic. LC, WA LC and WA O-DL). n.a., not applicable

Parameter	Qld SMC	Qld LC	NSW C-DL	Vic. LC	WA LC	WA O-DL	National herd (mean ± uncertainty)[A]
			Materials				
Purchased feed (kg/100 kg LW)	324.6	289.9	264.9	240.8	263.0	321.9	313.5 ± 26.7
Straw[B] (kg/100 kg LW)	n.a.	n.a.	23.1	n.a.	n.a.	69.9	18.9 ± 6.2
			Energy inputs				
Diesel (L/100 kg LW)	0.56	0.51	0.23	0.79	0.32	1.10	0.41 ± 0.29
Petrol (L/100 kg LW)	0.37	0.22	0.10	0.11	1.25	0.16	0.1 ± 0.08
LPG (L/100 kg LW)	0.27	0.28	1.94	0.17	0.17	0.35	0.2 ± 0.19
Electricity (kWh/100 kg LW)	15.45	22.21	16.83	22.03	20.97	2.95	16.0 (6.3–26.5)[C]
			Administrative and *financial services*				
Accounting, auditing and book keeping (AU$/100 kg LW)	1.5	1.6	1.4	1.7	1.7	2	1.7 ± 0.09
Automotive repairs (AU$/100 kg LW)	2.7	2.7	2.5	3.3	3	8.3	3.3 ± 1.04
Veterinary products and services (AU$/100 kg LW)	6.4	7.6	7	8.3	8.5	12.4	8.3 ± 0.89

[A]The uncertainty is reported as the 95% confidence interval, based on the mean, standard deviation and standard error. Values were assumed to follow a normal distribution.
[B]Deep-litter pigs only.
[C]Range in electricity values produced a positively skewed distribution, meaning that the s.d. gives no information on the asymmetry. Hence, the first and third quartiles were used as the upper and lower bounds of the range. Values were assumed to follow a triangular distribution.

We note that where effluent water is used as an input to cropping systems, this water could be attributed to the crop system rather than the pig system, noting the quality change that had occurred (Bayart *et al*. 2010). However, in the present study, beneficial effluent water reuse was not common and a conservative approach was applied by attributing all water consumption from effluent irrigation to the piggery system. For the purposes of reporting, fresh water consumption at the piggery was accounted for at the point where water evaporated from the system, which occurred either from the water supply system, directly from the sheds (including respiration losses from animals and evaporation of spilled drinking water, cleaning water, cooling water and excreted manure and urine), from the manure management system, or from the field after effluent or manure is applied to land. Irrigation water use associated with purchased commodities is described as 'ration irrigation off-site'. Irrigation water, used to produce purchased feed inputs, was modelled using methods described in Wiedemann *et al*. (2015*a*). Aggregated water use inventory data including details of the water supply system and efficiency are presented in Table 3.

Stress-weighted water use

The stress-weighted water use impact assessment method applied different stress weighting factors for different regions of Australia where the piggeries and meat processing plants were located, based on Pfister *et al*. (2009). For background products that may be sourced from many regions, we applied the Australian average WSI value of 0.402 for these sources. To calculate the stress-weighted water use, fresh water consumption in each region was multiplied by the relevant WSI and summed across the supply chain. The value was then divided by the global average WSI (0.602) and was expressed as water equivalents (H_2O-e; Ridoutt and Pfister 2010). Regional WSI values are shown in Table 3, and show two piggeries falling in regions of high water stress (WSI = 0.81–0.85) in the Murray–Darling basin of south-eastern Australia. Piggeries located in south-east Queensland and WA were in lower water stressed regions, though it should be noted that the WSI values were generated at a coarse level of resolution and some caution should be applied in their interpretation.

Meat processing

Meat processing inventory data were collected from four large pork processing plants over a 12-month period. Data were averaged and used for all supply chains as reported in Wiedemann *et al*. (2016*a*). Water inputs were 8050 L/1000 kg chilled pork and land areas for the meat processing plant were negligible because of the very high throughput of the plants and small land footprint. Packaging associated with the wholesale product was excluded.

Allocation

Allocation processes are required for several points in the feed and pig production systems and methods are described thoroughly in Wiedemann *et al*. (2016*a*), with a brief description provided here. In the feed supply chain, economic allocation processes were used to determine impacts to protein meals and oil products. Where rendered products such as meat meal were included in the feed supply chain, only the impacts associated with rendering the product and transporting it were attributed to pig production. Liveweight from young slaughter pigs and older, culled breeding animals was aggregated to avoid allocation. Manure and effluent were treated as residues after on-site treatment and no impact from pork production was attributed to this co-product. Meat yield was inclusive of edible offal, and impacts to co-products from meat processing were

Table 3. Piggery water resources for six case study supply chains and the Australian national herd

	Qld SMC	Qld LC	NSW C-DL	Vic. LC	WA LC	WA O-DL	National herd
Average annual rainfall (mm)[A]	650	650	589	369	650	530	n.a.
Piggery water supply							
Dam (%)	0%	17%	0%	0%	0%	27%	5%
Bore (%)	100%	83%	100%	100%	100%	73%	85%
River/Creek (%)	0%	0%	0%	0%	0%	0%	5%
Reticulated (%)	0%	0%	0%	0%	0%	0%	5%
Dam efficiency factor	n.a.	0.07	n.a.	n.a.	n.a.	0.5	n.a.
Bore efficiency factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total water supply (ML)	24.1	367.5	35.0	100.5	230	63.1	10 403
Water stress index values	0.017	0.021	0.815	0.8545	0.011	0.01	0.402

[A]Recorded for nearest major town.

allocated using economic value, resulting in a very small allocation (0.7%) to co-products, based on reported market values in 2014.

Scenario modelling

The impact of alternative housing and manure management systems on energy demand and fresh water consumption was investigated using a series of scenarios at one case study piggery. Scenario assumptions are described as follows.

Scenario 1 (S1): Qld LC – covered anaerobic pond (CAP) with combined heat and power (CHP) at the grower-finisher unit. The Qld LC piggery installed a CAP with CHP after the benchmarking period (2010–11) and this scenario was modelled using site data collected in 2014. Under current operational conditions, all effluent from the grower/finisher pigs is treated in a CAP, or 55% of total manure from the piggery. Approximately 54% of the biogas is converted to electrical and heat energy in the CHP engine and the remainder is flared. Following treatment in the CAP, effluent flowed into a secondary pond.

Scenario 2 (S2): Qld LC – CAP with CHP at the whole piggery. This scenario modelled the piggery operating at maximum potential for biogas production and energy recovery. It was assumed that all effluent produced at the piggery was treated in the CAP and all biogas produced was converted to electricity and heat in the CHP.

Scenario 3 (S3): Qld LC – DL. This scenario modelled a conversion of the sheds to use deep litter for the grow-out and finishing stages. Electricity consumption is lower for the deep litter system, as it uses natural ventilation, whereas the Qld LC CSF is tunnel ventilated. In addition, fresh water consumption will be lower as less is required for removing manure from the sheds and cleaning. Assumptions for each scenario are provided in Table 4.

Modelling and uncertainty analysis

Modelling was carried out using Simapro™ 8.0 (PRé-Consultants 2014). An uncertainty analysis was carried out to establish the robustness of the national herd results for fresh water consumption, stress-weighted water use, fossil fuel energy demand and land occupation (see Supplementary material). Model uncertainty for the national herd was assessed using Monte Carlo analysis in SimaPro 8.0. One-thousand iterations provided a 95% confidence interval for the results.

Table 4. Scenario modelling parameters

S1 = Qld LC-CAP-CHP at the grower-finisher unit, S2 = Qld LC-CAP-CHP for the whole piggery, S3 = Qld LC-DL for grow-out/finishing

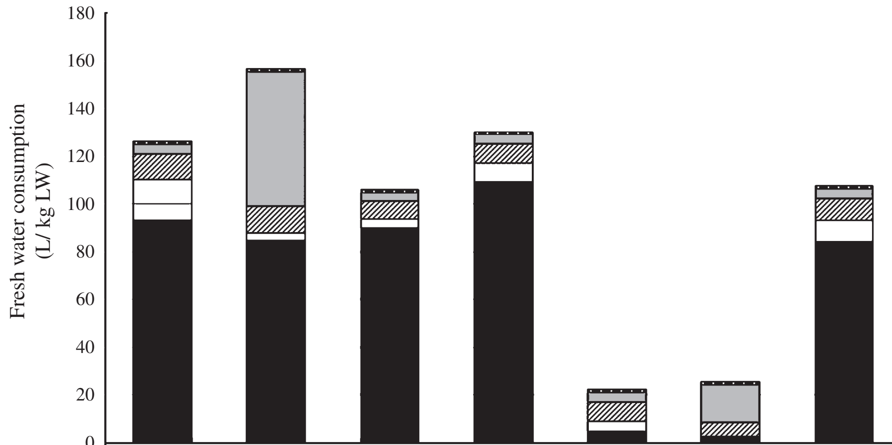
Scenario	S1 CAP-CHP	S2 CAP-CHP	S3 Deep litter
Proportion of total waste treated in uncovered anaerobic pond	45%	0%	24%
Proportion of total waste treated in alternative MMS	55%	100%	76%
Total water supply (ML)	367.5	367.5	262.8
Water supply (L/kg LW)	21.9	21.9	15.7
Biogas utilisation system			
Biogas yield (m^3 biogas/kg VS)	0.495	0.495	n.a
Proportion of methane in biogas	70%	70%	n.a
Methane density (kg/m^3)	0.668	0.668	n.a
Proportion of total biogas used in CHP to produce energy (remainder is flared)	54%	100%	n.a
Electrical efficiency CHP	30%	30%	n.a
Thermal efficiency CHP	45%	45%	n.a

Results

Farm-gate

Fresh water consumption ranged from 22.2 to 156.7 L/kg LW at the farm-gate, for the WA LC and Qld LC supply chains respectively (Fig. 2). Fresh water consumption was dominated by irrigation water associated with feed grain production for CSF in the eastern states, ranging from 54% to 85%, but not in WA where there is less irrigated feed available. Water supply losses, respiration, and cooling water evaporative losses ranged from 3% to 36% for the conventional piggeries, with the largest differences being between naturally ventilated piggeries (i.e. the Qld SMC) and piggeries with evaporative cooling (Qld LC, WA LC) where water use was higher. The Qld LC piggery also had higher water use because of evaporative losses from water supply dams located on the farm, which contributed some 32% of total water use at this farm.

Supply losses, respiration and cooling was a larger proportion of water use for the outdoor piggery (64%) because this piggery had high supply losses from open storages, and high cooling water use for wallows.



	QLD SMC	QLD LC	NSW C-DL	VIC LC	WALC	WA O-DL	National herd
Minor	1.1	1.3	1.3	0.7	0.8	1.0	1.0
Piggery water consumption	4.1	56.2	3.6	4.0	4.4	16.4	4.3
Manure management system	10.9	11.5	7.8	8.3	7.9	5.6	9.0
Effluent irrigation to low-value pasture	16.9	2.9	3.3	8.0	4.4	0.0	8.8
Feed ration irrigation	93.3	84.8	90.2	108.9	4.7	2.6	84.4

Fig. 2. Contribution to fresh water consumption per kilogram of liveweight for six case study supply chains and the Australian national herd.

Fresh water consumption (evaporation) losses from manure management systems ranged from 7.1% (Qld LC) to 35.6% (WA LC), and losses from land application were 2–20% from the conventional or deep litter piggeries. With similar diets, water use tended to be lower from deep litter compared with conventional finishing systems because the former required less water for cleaning. Total fresh water consumption at the WA O-DL supply chain (25.6 L/kg LW) was similar to the WA LC supply chains (22.2 L/kg LW) despite the very different production systems. The conventional piggery used larger amounts of water for cleaning and had high levels of productivity from the pigs. The outdoor piggery used large amounts of water for cooling (wallows) and losses from the water supply system were high, whereas cleaning water requirements were very low and herd performance was relatively lower, thus resulting in higher water use than may be expected.

Total fresh water consumption for the national herd was 107.5 ± 28.4 L/kg LW. The majority of water was associated with irrigated cereal grains produced in Australia and to a small extent, imported soy meal. Smaller amounts of water were consumed directly in pig production and processing.

Stress-weighted water use ranged from 6.6 to 167.5 L H_2O-e/kg LW, with the lowest values associated with the WA piggeries and the highest values from the NSW and Victorian piggeries. Stress-weighted water use was predominantly influenced by the region from which water was drawn, and to a lesser extent the volume of water used. The national average was 103.2 ± 32.4 L H_2O-e/kg LW.

Mean fossil fuel energy demand ranged between 12.9 and 17.4 MJ/kg LW (see Table 5 and Fig. 3). Feed production was the largest contributor to energy demand, ranging from 59% to 72%, followed by piggery energy use (28–41%). Among the conventional CSF, on-farm energy demand varied by 23% between the lowest and highest values, and total energy demand varied 26%. Deep litter and outdoor CSF were not found to be substantially different to conventional production with respect to energy demand, because the dominant impacts from feed production were similar in both housing systems and because of case study-specific aspects with these systems. Total fossil fuel energy demand for the national herd was 14.5 ± 1.1 MJ/kg LW, with 73% of impacts arising from feed production and the remainder from on-site energy use at piggeries.

Table 5. Resource use per kilogram of liveweight for six case study supply chains and the Australian national herd

per kg LW	Fossil energy (MJ LHV)	Fresh water consumption (L)	Water stress (L H_2O-e)	Crop land (m^2)
	Impact/Inventory categories			
Qld SMC	17.0	126.3	14.6	12.4
Qld LC	17.4	156.7	14.2	10.9
NSW C-DL	15.2	106.2	145.0	15.3
Vic. LC	14.7	129.9	167.5	12.9
WA LC	12.9	22.2	6.6	12.6
WA O-DL	13.7	25.6	6.8	16.1
National herd	14.5	107.5	103.2	16.1

Arable land occupation was lowest for the Qld LC supply chain at 10.9 m^2/kg LW and highest for the WA O-DL supply chain at 16.1 m^2/kg LW. Arable land occupation from the national herd was 16.1 ± 3.6 m^2/kg LW. Differences between supply chains occurred in response to relative feed conversion ratio (FCR) and differences in grain yield from region to region. The national average value was high compared with the CSF, primarily because the feed conversion was poorer than most of the CSF and because of the influence of production in South Australia, where yields tend to be lower than Victoria, NSW and Qld where many of the CSF were located.

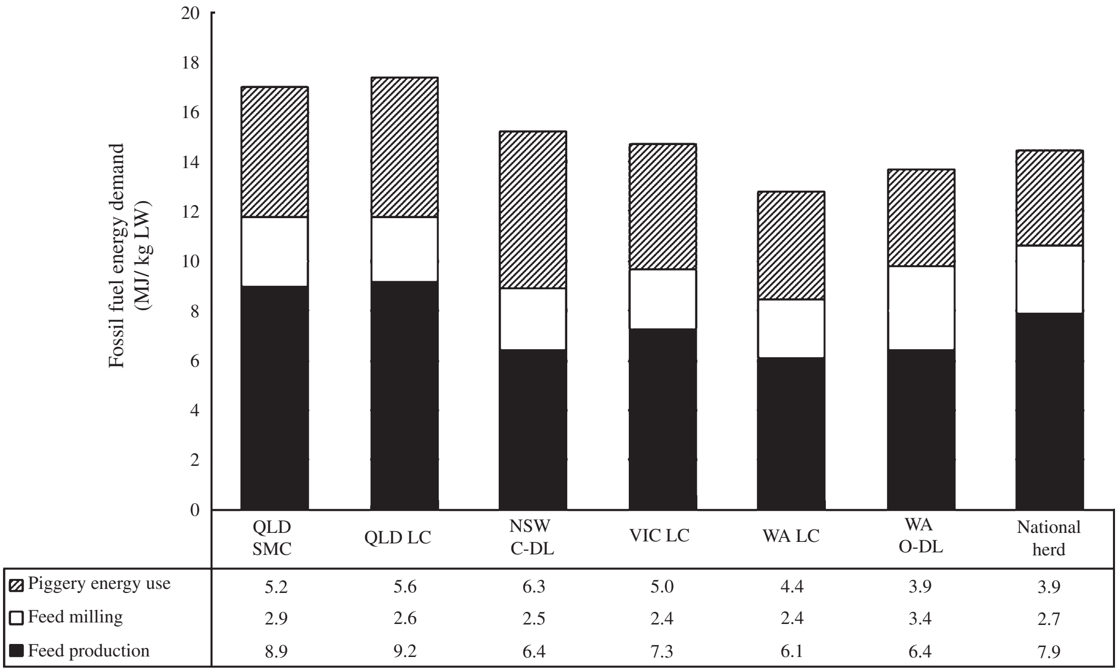


Fig. 3. Fossil fuel energy demand per kilogram of liveweight for six case study supply chains and the Australian national herd.

Table 6. Total fossil energy demand and fresh water consumption associated with the production of pork for the Qld LC scenarios

per kg LW	Impact/Inventory categories Fossil energy (MJ LHV)	Fresh water consumption (L)
Qld LC	17.4	156.7
(S1): Qld LC CAP-CHP	16.1	156.7
(S2): Qld LC CAP-CHP	13.1	156.7
(S3): Qld LC DL	14.6	113.2

Farm-gate scenario analyses

Table 6 shows the total fresh water consumption and fossil fuel energy demand for the Qld LC (baseline), and the alternative housing and manure management scenarios. Fossil fuel energy demand was reduced by 8%, 25% and 16% for the Qld LC – CAP with CHP (S1), Qld LC – CAP with CHP (S2) and Qld LC – DL (S3) respectively. Lower fossil fuel energy demand for the CAP with CHP scenario was the result of reduced electricity demand, and reduced gas use for heating at the piggery. Fresh water consumption remained the same as the baseline for the Qld LC – CAP with CHP (S1), Qld LC – CAP with CHP (S2) scenarios, but was reduced by 28% for the Qld LC – DL (S3) scenario because of the lower requirement for cleaning water.

Wholesale pork – national herd

Fresh water consumption from the national herd was 184 ± 43 L/kg wholesale pork and was dominated by irrigation water for feed (74%), followed by the farm (20%) and meat processing (6%). Stress-weighted water use was 172 L ± 53 H_2O-e/kg wholesale pork. Fossil fuel energy demand from the national herd was 27 ± 2.6 MJ/kg wholesale pork. Energy demand was dominated by feed production (46.8%), followed by piggery energy use (23%), feed milling (16.2%) and meat processing (14%). Arable land occupation from the national herd was 25.9 ± 5.5 m^2/kg wholesale pork.

Discussion

This study presents the first comprehensive analysis of resource use associated with Australian pork production using LCA, and one of few pork LCAs covering these impact categories internationally. Between CSF, impact intensity varied in response to housing system, feed efficiency and regional characteristics such as crop yields and the prevalence of irrigation water use in rations. Results were sensitive to a range of assumptions regarding feed grain production and diets and these are explored in the following section.

Sensitivity to model assumptions

Across most case studies and most impact categories, feed use was the greatest source of impacts, which was similar to studies investigating other environmental impacts in pig production systems (McAuliffe *et al*. 2016). As a consequence, the model was sensitive to several feed-related assumptions. Few data were available to compare energy, water or land occupation associated with different feed commodities. Comparing GHG emissions as a proxy for energy, we found few substantial differences between major grain inventory processes (derived from the AustLCI – Life Cycle Strategies 2015) and other Australian studies (Wiedemann *et al*. 2010; Brock *et al*. 2012). This suggests a reasonable level of agreement between grain LCI data for major Australian processes, where most energy sources are dependent on fossil fuels. To explore the impact of the inclusion rate of different cereal grains within rations, we compared wheat and sorghum-based diets for Queensland, and wheat or barley diets in southern/western regions. We found no substantial effect on energy, water or arable land occupation from changing grain types between the major cereal grains. However, the inclusion rate of soybean meal did influence energy use, fresh water consumption and stress-weighted water use because imported soymeal is energy and water intensive. With all other factors remaining equal, diets utilising lower proportions of soymeal were found to have lower impacts.

Fresh water consumption and stress-weighted water use were sensitive to assumptions regarding irrigation rate and irrigation region. Inter-annual variation in irrigation rates in Australia can be high and thus water attributed to grain processes may differ from year to year. We found water use associated with grains to vary from 1.8 to 2.8 ML/ha between a low water availability year (2010) and a high water availability year (2008). We found that fresh water consumption varied by 22% below and 5% above the national herd value between high and low water use 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, and estimates would be improved if annual, catchment specific WSI values were available. Arable land occupation was sensitive to grain yields. Inter annual variation in crop yields in Australia can be high and thus arable land attributed to grain processes differ from year to year. For example, national wheat yields varied from 2.0 (2006) to 0.9 t/ha (2007) (ABS 2013) with the variation being a response to rainfall in each given year. Taking this variability into account, arable land occupation ranged from 27% below to 33% above the national herd value when grain produced in these years was modelled. Considering the sensitivity of water and land occupation results to a specific year, benchmarking results require frequent updating to remain current. Alternatively, averaging results over a longer time period (3–5 years) is expected to produce more stable results. This inter annual variation is a particular feature of Australian systems, that are heavily influenced by climate variability. Further research is required to understand the impact of this variability on resource demand for grain crops and grain users such as pork.

Resource use and impact intensity

Fossil fuel energy demand ranged between 12.9 and 17.4 MJ/kg LW at the farm-gate, and these results were similar to several European studies (Basset-Mens and van der Werf 2005; Dourmad *et al*. 2014; Mackenzie *et al*. 2016). Energy demand differed in response to energy efficiency at the piggery, housing type and the energy intensity of the diet. Energy efficiency research has identified substantial differences between farms with different cooling systems in particular (McGahan *et al*. 2015), suggesting that on-farm efficiency improvements are possible, resulting in both environmental improvements and cost savings. Interestingly, energy demand for pigs raised in the WA O-DL system, were not lower than comparative conventional production (WA LC). Although on-farm energy demand was slightly lower for the O-DL system, this did not compensate for the higher feed-related impacts associated with poorer production efficiency (pigs weaned per sow per year and FCR), which was similar to the finding of Dourmad *et al*. (2014).

In the eastern states, irrigation water embedded in feed dominated fresh water consumption, rather than drinking water at the piggery. Irrigation water varied widely between regions, and was up to 86% lower in the WA supply chains because of the small amount of irrigation used for grain production in this state. Irrigation use and volume in grain production are not factors that can be influenced by pig producers, though water use associated with grain may be reduced by improving herd FCR and this is one opportunity available to the industry to reduce water use. Herd FCR is a major driver of production costs in pig production, and is the subject of considerable focus from both producers and researchers, via improvement in reproductive efficiency, growth rates, nutrition and animal health. These improvements are expected to yield both production benefits and benefits regarding resource use efficiency and the environment, provided trade-offs do not occur.

No LCA studies were found reporting fresh water consumption using comparable methods to the present study, though several water footprint studies have been completed (Mekonnen and Hoekstra 2012; Gerbens-Leenes *et al*. 2013; de Miguel *et al*. 2015). These studies report 'green', 'blue' and 'grey' water, of which 'blue' water is broadly comparable to fresh water consumption in the present study, though calculation methods are quite different. Fresh water consumption in this study (22.2–156.7 L/kg LW) was considerably lower than the 257–405 L/kg (converted to LW basis) reported by Mekonnen and Hoekstra (2012) and de Miguel *et al*. (2015). These studies found that intensive systems used less water per kg LW than extensive systems due to the increased productivity of these systems. An opportunity may exist to improve water-use efficiency by improving the beneficial utilisation of effluent at piggeries for crop production. Where this water can be used to replace clean irrigation water, the apparent fresh water consumption of the piggery could be reduced by up to 18% by allocating this water to the end-user (crop) rather than the piggery. Provided irrigation is managed within sustainable limits, the added nutrients contained in pig effluent can also reduce reliance on synthetic fertilisers in cropping systems without substantial environmental burdens, though further research is required in this area to understand eutrophication risks associated with pig production.

Between CSF, regional water stress was found to have more influence on the impact of water use than the total volume used; suggesting the location of water use is a more important factor governing impact on the environment than volume used. The highest values were seen for the NSW and Vic. CSF, were stress-weighted water use was higher than volumetric water use in response to the high levels of water stress in the lower Murray–Darling basin. Although this was a reasonable representation, we note that the WSI values of Pfister *et al*. (2009) are of coarse resolution, and may under-estimate water stress in other regions. Seasonal water stress should also be taken into account to understand impacts more thoroughly. Further research is required to improve this analysis and apply updated methods developed in this area.

No studies were found reporting stress-weighted water use for pork production, but compared with beef production in eastern Australia where stress-weighted water use ranged from 2.0 L-361.7 L H_2O-e/kg LW (Wiedemann *et al*. 2016*b*) from

CSF, the stress-weighted water use from piggeries covered a smaller range of values.

Land occupation was dominated by feed production, whereas the land occupied for the piggery itself was insignificant because of the very high density of livestock on relatively small land areas. Arable land occupation for CSF ranged between 10.9 and 16.1 m^2/kg LW, which was generally higher than values found in the literature, which ranged from 4.1 to 12.1 m^2/kg LW (Basset-Mens and van der Werf 2005; Dourmad *et al*. 2014; Bava *et al*. 2015; González-García *et al*. 2015). These comparison studies were predominantly from northern European countries, where grain yields are significantly higher than Australia, explaining the difference between these results and the present study.

Improvement scenarios

Energy generation from manure has been identified as an opportunity to improve efficiency in European systems (Nguyen *et al*. 2010). Scenario modelling in the present study revealed moderate reductions in energy demand for conventional housing systems, where the CAP and CHP were installed or deep litter housing systems used. One scenario (scenario 1) was based on an actual installed system at the case study piggery and therefore provides insight into the likely energy demand reduction under commercial conditions. The CAP with CHP system was installed at the grower-finisher site, where the largest amount of manure is produced. At this site, the heat produced by the CHP was not fully utilised, because it was logistically difficult to transport heat from the grower-finisher site to the breeder site where most heat is required. This is a common problem for multi-site piggeries and may limit the capability of CHP units to meet the heat requirements of the piggery. We also observed that transporting electricity from the generation site to other sites was logistically difficult; in some instances requiring the installation of privately owned power networks with high capital costs. Excess electricity was also not easy to sell by exporting to the grid at the Qld LC site, and at the time of performing the analysis, cost effective agreements had not been established with local power providers. As a result, excess biogas was flared to destroy the methane, but the energy potential was not utilised. Where we modelled all manure being treated in the CAP with CHP system (scenario 2), total energy demand per kg LW was reduced by 25%, to 13.1 MJ/kg LW.

We modelled deep litter housing for the grow-out and finishing stages. This scenario also provided substantial reductions in energy demand (16%) and fresh water consumption (28%). The reduction in energy demand is primarily a function of reduced electricity consumption using the deep litter housing system, as it was not tunnel ventilated as the conventional system was. The decrease in fresh water consumption was primarily influenced by the reduction of cleaning and cooling water at the piggery. According to the National Greenhouse Gas Inventory, 6.5% of manure was treated in CAP or engineered digesters in the 2010–2013 period (derived from Commonwealth of Australia 2015). A large proportion of manure is currently treated in anaerobic effluent systems (71.4%, see Wiedemann *et al*. 2016*a*; Supplementary material). The introduction of government payments in Australia to reduce greenhouse gas emissions has made installation of anaerobic digestion and energy production equipment much more cost effective, as evidenced by the substantial number of Australian piggeries installing this equipment.

Incremental improvements in environmental performance may also be achieved by improving feed efficiency in the long-term. Whole herd FCR (LW) ranged from 2.4 to 3.2 in the present study with an average of 2.9. This corresponds well to the national overall average of 2.96 reported by the industry in 2010–2011 (Pork CRC, unpubl. data). Feed efficiency has improved in Australia, with a 5% reduction in FCR being recorded between 2010 and 2015 (Pork CRC, unpubl. data). Provided diets and other inputs remain similar, this improvement should correspond to lower energy, water and arable land requirements for pork production, reducing impacts on primary resources. As feed is also a major production cost, improvements in FCR provide economic and environmental benefits. Though not studied here, reduced crude protein diets have been shown to result in lower environmental impacts in pig systems elsewhere in the world (McAuliffe *et al*. 2016) and although this approach tends to aim at reducing greenhouse gases (i.e. Wiedemann *et al*. 2016*c*) and nutrient-related impacts, it may also offer opportunities to reduce resources if FCR is also improved or if the reliance on high impact commodities such as soymeal is reduced. Further analysis of this would be beneficial to industry. Considering the significance of feed impacts, improvements may also be achieved by utilising higher proportions of by-product feeds in pig rations. Pigs have an important role in utilising low value by-products or waste products from the human food supply chain and further investigation into the environmental significance of including these by-products is warranted.

Wholesale pork – national herd

When impacts were assessed through to the point of a wholesale ready product, impacts were dominated by feed production (63–99% of total impacts) and on-farm production (0.5–23%), whereas meat processing tended to be a smaller contribution (0.5–14%). Because of the mass losses associated with meat processing, reported impacts per kilogram of pork rose substantially compared with LW. Comparison pork results that included meat processing were more difficult to find. Mackenzie *et al*. (2016) and Mekonnen and Hoekstra (2012) provide results on an expected carcass weight basis but they do not include impacts from meat processing. González-García *et al*. (2015) included the role of meat processing and, similar to the present study, found the contribution to generally be <5%. These authors reported fossil energy demand of 30.9 MJ/kg edible product, whereas arable land occupation was 8.5 m^2/kg edible product, calculated with an edible yield of 62% of carcass weight. The wholesale product used as the FU in our study was a 'bone-in' product, with an estimated edible yield of 85%. Relative to carcass weight, this resulted in 69% edible yield in the present study. This slightly higher value may be the result of skin and subcutaneous fat, which were included in the edible portion on some cuts. When impacts were recalculated and reported per kilogram of edible meat (bone-free), they were 32 MJ energy, 212 L fresh water, 203 L H_2O-e and 31 m^2 land/kg pork, which was similar to the energy values reported by González-García *et al*. (2015) whereas land was much higher in the present study. Regional averages for beef and lamb produced in eastern Australia showed lower energy demand for lamb and similar energy demand for grass fed beef, whereas stress-weighted water use (108.5–169.4 L H_2O-e/kg edible meat) and arable land use was lower for lamb and grass-fed beef (Wiedemann *et al*. 2015*c*) compared with the present analysis of Australian pork. The lower stress-weighted water use associated with lamb and beef is a function of production in lower water-stressed regions, compared with the high impacts associated with irrigation water use in the pork supply chain. The lower requirement for arable land in lamb and beef production reflects the predominance of rangeland grazing in these industries, which relies on non-arable land. All impacts trended higher than chicken meat production in two Australian regions (Wiedemann *et al*. 2017), largely in response to the higher feed requirements for pork compared with chicken meat.

Conclusions

This study provides the first case study and national analysis of energy, water and land occupation from Australian pork production using LCA. Australian pork tended to utilise similar amounts of fossil fuel energy and smaller volumes of fresh water than northern hemisphere production systems. However, Australian production typically had larger requirements for arable land because of the lower yields in Australian cropping regions. The impact on water use was found to be lower than the volumetric volume may suggest in several regions, but not for the national average production. However, noting the coarse scale of the WSI values applied, further research is required to apply new water stress impact methods. The study found that feed production is the dominant contributor through to production of a wholesale product for energy, water and land occupation. Considering the importance of feed impacts for all impact categories, FCR is an important production metric influencing the environmental efficiency and cost of production for pork and improvements in this metric are expected to reduce resource-related impacts. Alternative manure management systems that produce energy from biogas and in some cases, alternative housing systems, may also be used to reduce energy and water from pork production. Considering that changes may occur in system efficiency, FCR, manure management and grain production over time, and considering the impact of seasonal variations, it is recommended that benchmark results are produced at 5-yearly intervals to maintain the currency of the results.

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