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AUSTRALIAN Pork

Trends in environmental impacts from the pork industry

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Executive Summary

Over the past four decades, major changes have occurred in Australia's pork industry, affecting productivity and the environmental impacts from production. Using a life cycle assessment (LCA) approach with a 'cradle-to-farm gate' boundary, the changes in greenhouse gas (GHG) emission intensity and key resource use efficiency indicators (fresh water consumption, water stress, fossil fuel energy demand and land occupation) were determined at decade intervals between 1980 and 2010. Results for 2020 were projected from trends identified in the 1980 to 2017 data. Impacts were reported per kilogram of pork (live weight – LW) produced in each decade.

The analysis showed that over the four decades since 1980 there has been a decrease in GHG emission intensity, excluding land use (LU) and direct land use change (dLUC) emissions, of 69% from 10.6 to 3.3 kg CO2-e kg liveweight (LW)-1. GHG emissions associated with LU and dLUC were estimated to have declined by 89% since 1980. Fresh water consumption decreased from 441 L kg LW-1 in 1980 to a projected 90 L kg LW-1 in 2020. Water stress followed a similar trend, decreasing from 287 L H2O-e LW-1 in 1980 to a projected 57 L H2O-e LW-1 in 2020. Fossil energy use decreased from 34 MJ kg LW-1 in 1980 to a projected 14 MJ kg LW-1 in 2020. Land occupation decreased by 63% from 31 m2 kg LW-1 in 1980 to a projected 11 m2 kg LW-1 in 2020.

Improvements were principally driven by improved herd productivity, changes in housing and manure management, and improved feed production systems. In the pig production system, improved herd and system efficiency led to improved feed conversion ratio, resulting in lower feed requirements, and reduced manure production. This was partly also associated with reduced feed wastage, which had a disproportionally larger effect on reducing manure GHG emissions.

Concurrently, improvements in feed grain production systems resulted in lower impacts per tonne of feed grain produced. This was related to reduced tillage, higher yields and a decrease in the proportion of irrigation water used for grain production. This paper discusses the prospects and challenges for further reductions in greenhouse gas intensity and gains in resource use efficiency for Australian pork production. This study has shown that ongoing changes and improvements in production efficiency have resulted in large gains in environmental performance in the Australian pork industry.

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1 Introductory Technical Information

In response to increased demand for pork, global production increased by a factor of 4.5 between 1961 and 2014, from 24.8 to 112.3 million tonnes (Ritchie and Roser, 2018). The OECD (2018) estimates that an average of 117,354 kilo-tonnes of pig meat were consumed globally each year between 2015 to 2017, with consumption projected to increase by a further10.2% by 2027. This historic increase in pork consumption, and projected future increase in consumption, raises the importance of understanding environmental impacts from pork production and how these impacts have changed over time. Globally, livestock production accounts for 14.5% of anthropogenic emissions of greenhouse gases (GHGs) (Gerber et al., 2013), with pork supply chain emitting approximately 0.7 gigatonnes CO2-eq per annum, equating to 9% of the livestock sectors' total emissions (MacLeod et al., 2013). This is slightly higher than chicken production (0.6 gigatonnes CO2-e per annum), but significantly lower than beef and bovine dairy production combined (4.6 gig-tonnes CO2-e per annum) (Gerber et al., 2013).

In Australia, pig production has transitioned from small farm enterprises to large scale, specialist pig farming operations in the second half of last century (Gardner et al., 1990), which has profoundly influenced production efficiency (e.g. weaning rates, live weight produced per sow, average daily gain (ADG) and feed conversion ratio FCR) and potentially the environmental impacts of the industry. The pork industry has increased total production substantially since 1980, primarily because slaughter numbers and slaughter weights have increased (ABS, 2018b) despite breeding herd numbers remaining fairly constant (ABS, 1999, ABS, 2001, ABS, 2012a, ABS, 2018a). This demonstrates a substantial improvement in herd productivity, with more pigs per sow being produced, and higher turnoff of pork relative to breeder numbers. Recent analyses have shown that pork production is continuing to increase, and this trend is expected over the next five years (ABARES, 2017), though recent grain prices may delay this trend.

Herd productivity, and particularly feed conversion ratio, is a key driver of change in environmental impact. Wiedemann et al. (2016b) showed that production efficiency, and specifically whole herd FCR, explained 88% of the variation in GHG emissions from conventional Australian piggeries using the same manure management system (MMS). The strong association with whole herd FCR can be explained because this factor influences both upstream impacts associated with feed production, and downstream impacts associated with manure emissions. Whole herd FCR is also an aggregate indicator, being influenced by many herd production factors including weaning rate and growth rates, and also by system efficiency factors such as the proportion of feed wasted. Wiedemann et al. (2017) showed feed production was the largest contributor to water, energy and land resource use associated with Australian pork production, further highlighting the importance of feed conversion ratio as the most important production metric for reducing the resource use. Further to this, Reckmann and Krieter (2015) and Nguyen et al. (2010) variously demonstrated that improved feed conversion ratio, improved breeding efficiency, improved growth rates and increased turn-off weight reduced environmental impacts per kilogram of pork produced. Noya et al (2017) has proposed several feeding strategies to reduce environmental impacts of pork, of which the introduction of local ingredients seemed the most promising alternative. Nguyen et al., (2010) and Groen et al. (2016) showed that fossil energy use and GHG emissions associated with pork production could be reduced by taking improvement measures in feed use and manure management practices. Furthermore, pig housing and manure management systems (MMS) substantially influence the levels of GHG emissions emitted by pork production (Philippe and Nicks, 2015, Chadwick et al., 2011, Wiedemann et al., 2016b), suggesting that changes in these areas will also influence impacts from pork production.

There have been several studies investigating environmental trends in livestock production systems. These studies include beef (Capper, 2011, Wiedemann et al., 2015), sheep (Benoit and Dakpo, 2012), dairy (Capper et al., 2009) and pork production (Vergé et al., 2009, Boyd et al., 2012). Wiedemann et al. (2015) showed a 14% decrease in GHG emission intensity, 42% decrease in land use (LU) and direct land use change (dLUC) emissions, 65% decrease in water consumption and 19% decrease in land occupation associated with Australian beef production, over the three decades since 1981. However, fossil energy use increased by 186% over the same time period in response to intensification of the beef industry. Reductions in GHG emissions were largely due to efficiency gains through heavier slaughter weights, increases in growth rates in grass-fed cattle, improved survival rates and greater numbers of cattle being finished on grain, which increased growth rate and slaughter weight.

A similar trends analysis of Australian pork production has not been done, and consequently there is a knowledge gap around the change in impacts over time and the major influences on environmental impacts in the industry. Using an LCA approach, the present study investigated the trend in environmental performance of the Australian pork industry, focusing on GHG emissions and resource use in 10-year intervals from 1980 to 2010, and projected impacts for 2020.

2 Research Methodology

2.1 *Materials and methods*

2.1.1 Goal and scope

This study was an attributional LCA investigation of the environmental impacts of national Australian pork production from 1980 to 2020, to determine trends in environmental impacts and changes that have affected environmental performance over the past four decades. The study was completed to provide this information to the pork industry, research community and the general public.

The study investigated GHG emissions using the Intergovernmental Panel on Climate Change (IPCC) AR4 global warming potentials of 25 for CH_4 and 298 for N_2O (Solomon et al., 2007) as applied in the Australian National Inventory Report (Commonwealth of Australia, 2015). GHG emissions arising from land use (LU) and direct land use change (dLUC) were calculated and reported separately following the guidance of ISO/TS 14067. Energy demand was assessed using the fossil fuel energy demand method (Frischknecht et al., 2007), and fresh water consumption and water stress (Pfister et al., 2009) were also assessed. Modelling was conducted using SimaPro 8.5 (Pré-Consultants, 2018).

System boundaries and reference flow
The study examined the primary production system (i.e. cradle to farm gate) using a reference flow of one kilogram of live weight (LW) on-farm, immediately prior to processing. The pig production system included production of feed ingredients and all on-farm processes involved in the production of pigs through to being ready for meat processing. The herd was modelled at 10 year intervals, with each period reflecting production from the preceding two years.

2.1.2 Inventory data

2.1.2.1 Australian national herd data

A model of the Australian pig herd was developed for each time period using national herd statistics (see Table 1) and herd performance data (Table 2). Herd numbers were accessed from the annual survey of Australian farms (ABS, 1999, ABS, 2001, ABS, 2012a, ABS, 2018a), which included breeder and grower pig numbers. Data were averaged for two-year intervals at the end of each decade, to smooth market fluctuations. An independent dataset of the total number of pigs slaughtered, and total carcass weight (ABS, 2018b) was available to determine the total output of the herd.

Table 1 National pig herd data based on Australian primary data

Category	**Units**	**1980**	**1990**	**2000**	**2010**	**2020** [c]
Total sow numbers [a]	Pig/yr	272273	301539	264337	236936	225002
Total boar numbers [a]	Pig/yr	21066	21745	15977	9240	5678
Total slaughter pigs [b]	Pig/yr	3784400	4944600	5025950	4558400	4959657
Total slaughter weight produced (Dressed Weight, DW) [b]	Tonne	211636	314741	363282	331203	389187

[a] (ABS, 1999, ABS, 2001, ABS, 2012a, ABS, 2018a), [b] (ABS, 2018b), [c] projected from 1980-2017 data.

2.1.2.2 Herd performance, diets, and feed use

Based on the national inventory numbers and a parameterised herd model, a livestock balance was developed for the Australian pig herd. Inventory data (Table 1) provided the total number of breeding pigs, and the total output in terms of numbers and carcase weight. Using parameters collected from industry surveys (Cleary and Ransley, 1994, Cleary and Meo, 1997, Cleary and Meo, 1999a, Cleary and Meo, 2000, Cleary and Godfrey, 2002, Cleary et al., 2003, McElhone and Philip, 2004, McElhone and Philip, 2005, Dowling, 2006, Walsh and Bottari, 2008, APL, 2010, APL, 2011, APL, 2012, Wiedemann et al., 2016b, Wiedemann et al., 2017), a livestock balance was developed for the herd that accounted for breeder mortality, breeder replacement rates and herd FCR of pigs from birth to slaughter. The average age of finisher pigs was determined by dividing average sale weight minus birth weight, by average daily gain (ADG). Pigs sold per sow per year was assumed to be the total number of pigs slaughtered divided by the total number of sows (both reported in Table 1).

Feed intake and diets were determined for each decade for each major production region in Australia, via consultation with industry nutritionists. Feed waste estimates were determined from Willis (1999), Taylor and Clark (1990) and Roese (1990). Four standard diets were modelled for the main production regions in the national herd, after Skerman et al. (2015). Diet A was considered representative of the NSW and VIC region and Diet B was used for the QLD region. Diet D was considered representative of the WA region; however, the mung bean diet component was replaced by lupins, which was more representative of data collected by the authors from major WA piggeries (S. G. Wiedemann, unpubl. data). Diet D was also considered representative of the SA region; however, the mung bean component was replaced by field peas, which was more representative of data collected by the authors from major piggeries in this region (S. G. Wiedemann, unpubl. data). State diets were aggregated to produce national rations (Table 3). Historic diets were determined by consulting with industry nutritionists (for further detail refer to Supporting Information, Section: National standard diets). Using these data, the herd was modelled each decade using Pigbal 4 (Skerman et al. 2015) to determine feed use, FCR and average daily gain (ADG).

Table 2 National Australian pig herd performance data

Category	Units	1980	1990	2000	2010	2020 [e]
Weaning age [a]	days	34.3	24.5	21	23.2	22.3
Litters per sow per year [a]	#	2.1	2.2	2.2	2.3	2.3
Pigs born alive per Sow per Year [a]	#	19.6	22.9	22.6	24.8	25.8
Pigs weaned per Sow per Year [a]	#	14.7	19.9	19.4	21.5	23.1
Pigs sold per Sow per Year [a]	#	13.9	16.4	19.0	19.2	22.0
Liveweight sold per sow per year [b]	kg	1022.4	1373.7	1807.9	1839.5	2276.3
Average sale weight of finisher pigs [c]	kg	75	84.9	96	95.6	103
Average age of finisher pigs [c]	days	144	146	161	150	138
Average daily gain (wean-finisher slaughter) [d]	gram/day	500	568	586	636	693

FCR (grower herd) [d]	FCR	3.5	3.1	2.9	2.5	2.3
FCR (whole herd) [a]	FCR	5.19	4.4	3.6	3.2	2.9

[a] Literature value derived from multiple sources, see supporting information, [b] ABS (2018b), ABS (1999, 2001, 2012a, 2018a), [c] (ABS, 2018b), ABS (2017) dressing percentage was altered by 0.5% between decades from 74.5% in 1980 to 76.5% in 2020, [d] modelling using PigBal (Skerman et al. 2015), [e] projected from results for 1980-2017.

Table 3 Ration components and diet properties for pig feed over the time period 1980 to 2020

Note: diets represent a weighted average of breeder, weaner, and grower finisher diets, averaged across all major production regions

Ration component	**Unit**	**1980**	**1990**	**2000**	**2010**	**2020**
Barley	%	10.84	17.55	19.96	22.13	22.01
Sorghum	%	16.19	12.34	10.72	14.31	14.26
Wheat	%	48.38	47.19	49.75	45.14	45.48
Lupins	%	1.79	2.05	2.64	1.54	1.44
Field peas	%	2.75	3.7	3.91	3.34	3.11
Bloodmeal	%	2.07	0.93	1.12	1.10	1.10
Meat and bone meal	%	11.55	8.93	3.62	2.83	2.72
Canola meal	%	0.0	0.6	1.0	3.2	3.8
Soymeal	%	0.5	2.08	3.8	3.4	2.9
Other protein meal	%	3.57	2.37	1.2	0.5	0.5
Vegetable oil	%	0.86	0.82	0.48	0.37	0.36
Low-cost additives	%	1.34	1.19	1.44	1.44	1.43
High-cost additives	%	0.16	0.25	0.36	0.70	0.89
Feed dry matter	%	89.02	88.8	88.47	88.48	88.54
Diet ash	%	6.71	5.78	4.40	4.18	4.19
Crude protein	%	19.64	18.36	17.24	16.82	16.86
Dry matter digestibility (DMD)	%	76.94	79.46	81.72	83.31	84.24
Feed wastage	%	19.4	15.7	11.4	7.9	7.4

2.1.2.3 Australian pig housing and manure management systems

The proportion of pigs across Australia produced in different housing types influences resource use and the type of manure management system (MMS) used, with both being significant contributing factors to GHG emission intensity and resource use. In Australia, pig housing can be categorised into three broad types: outdoor, conventional and deep litter (Wiedemann et al., 2016b). As shown in Table 4, outdoor housing has one MMS, deep litter housing has a limited number of MMS, while conventional housing can have several different MMS, including: effluent ponds, anaerobic digesters, short hydraulic retention time (HRT) storage systems and solid separation with stockpiling or composting. Housing and MMS for the years 1990-2014 were reported in the Australian NIR (Commonwealth of Australia 2015), and were applied in the study. Housing type and MMS for 1980 was determined from Ballantyne and Wrathall (1984) and personal communications with industry researchers (K Casey, pers. comm.). Housing and MMS for 2020 was determined using data from Australian NIR (Commonwealth of Australia 2015) and Wiedemann and Watson (2018). For further detail on MMS refer to Appendix 1 - Supporting Information, Section: Housing and manure management systems.

Table 4 Proportion of manure treated in different manure management systems in the Australian herd from 1980 to 2020

Housing system	MMS	Units	1980 [c]	1990	2000	2010	2020 [d]
Outdoor	Spread to pasture	%	5.0%	3.0%	5.0%	5.1%	5.9%
Deep litter [(a)]	Solid storage	%	0.0%	1.0%	24.8%	21.7%	19.7%
Conventional	Effluent pond [(b)] (Uncovered anaerobic pond)	%	84.4%	90.0%	66.4%	63.8%	56.6%
	Anaerobic digester / Covered pond	%	0.0%	0.4%	0.3%	6.2%	15.6%
	Short HRT tank storage (< 1 month)	%	9.4%	2.0%	1.4%	1.4%	1.4%
	Solid separation and solid storage	%	1.2%	3.6%	2.1%	1.8%	0.8%

[a] 5% of VS is assumed to be lost in the primary system (Wiedemann et al., 2014). [b] Secondary MMS from covered pond/digester is an uncovered pond, and 75% of VS is assumed to be lost in the primary system (Wiedemann et al., 2014). [c] Authors estimation from personal communication with industry experts. [d] Authors projection from NIR (Commonwealth of Australia, 2015) and Wiedemann and Watson, (2018).

2.1.2.4 Manure production and management emissions

Manure production was modelled from predicted manure excretion and feed waste using Pigbal 4 (Skerman et al. 2015). Briefly, this model applied a mass-balance approach to predict excreted nitrogen, and the dry matter digestibility approximation of manure production method to determine excreted volatile solids. Feed waste is a predicted input to the manure stream. Manure emissions were determined using the emission factors outlined in the Australian NIR (Commonwealth of Australia 2015) (key factors summarised in Appendix 1 - Supporting Information, Section: Housing and manure management systems) and were inclusive of system losses. In accordance with Wiedemann et al. (2016b) manure nutrients from effluent and spent litter were included as an input to the modelled cereal crop systems used in the feed inventory, which reduced fertiliser requirements by <1%.

2.1.2.5 Feed grain system inputs

Feed grain inputs were modelled using inventory data from Wiedemann et al. (2016b) and the Australian National Life Cycle Inventory Database (AusLCI) (ALCAS, 2017). Feed grain processes were developed for the time periods from 1980-2000 to reflect crop yield, crop irrigation and tillage practices from national statistics (ABS, 2012b, Watson et al., 1983, Llewellyn et al., 2012, ABS, 2011, ABS, 2005-2018). Fuel use was adjusted in response to changes in tillage and to reflect changes in engine efficiency for agricultural equipment over the time period. Fertiliser and herbicide usage over the time period was determined from national purchase data (Dept. Env and Energy, 2006). A more detailed description of these factors is provided in Appendix 1 - Supporting Information, Section: Feed Production Data. Additionally, the total land occupation for crop production was determined from reported crop yields each decade (ABS, 2012b) (refer to Appendix 1 - Supporting Information, section: Feed Production Data).

2.1.2.6 *General services, water and energy*

Operational inputs including purchased material, energy and water are reported per 100 kg LW pork ready for slaughter (Table 5). Trends in on-farm piggery energy use were determined from incomplete datasets taken from Pigstats (Cleary and Meo, 1998, Cleary and Meo, 1999b, Cleary and Godfrey, 2002, Cleary et al., 2003) and Wiedemann et al. (2016b). These datasets showed energy use was 19.7% higher for the three years to 2000 compared to 2010, for conventional piggeries, and this difference was used to predict an increase in energy demand of 19.7% for each decade back to 1980. The inventory values used for diesel, petrol, LPG and electricity usage in both deep litter and outdoor production systems were based on Wiedemann et al. (2016b), modified to reflect improved engine efficiency using the same method as in feed production.

In accordance with PigBal 4 (Skerman et al., 2015), methods from Wiedemann et al. (2012) and Taylor et al. (1994) were used to estimate cleaning water, drinking water and cooling water use (refer to Appendix 1 - Supporting Information, Section: Direct Piggery Water Use, for further information). The projected decrease in piggery water use was attributed to increases in water recycling in conventional piggeries as well as improvement to drinkers and water management (Holyoake et al., 2018, Apostolidis et al., 2011, Gonyou, 1996, Muhlbauer et al., 2011).

Table 5 Aggregated general services and energy inputs for national pig production (on-farm) for each decade from 1980 to 2020.

Input	Parameter	Units	1980	1990	2000	2010	2020
Materials	Purchased feed (as fed)	kg 100kg LW^{-1}	519.00	440.10	361.90	318.90	288.90
Services, conventional	Diesel	L 100kg LW^{-1}	0.59	0.55	0.53	0.51	0.49
	Petrol	L 100kg LW^{-1}	0.25	0.24	0.23	0.22	0.21
	LPG	L 100kg LW^{-1}	0.45	0.39	0.34	0.28	0.22
	Electricity	kWh 100kg LW^{-1}	35.34	30.96	26.59	22.21	17.83
	Piggery Water use	L kg LW^{-1}	93.65	48.63	28.34	23.08	16.52
Services, deep litter/outdoor	Diesel	L 100kg LW^{-1}	1.27	1.20	1.14	1.10	1.07
	Petrol	L 100kg LW^{-1}	0.18	0.17	0.17	0.16	0.16
	LPG	L 100kg LW^{-1}	0.56	0.49	0.42	0.35	0.28
	Electricity	kWh 100kg LW^{-1}	4.69	4.11	3.53	2.95	2.37
	Piggery Water use	L kg LW^{-1}	22.43	20.92	14.79	12.88	11.77

2.1.2.7 *Land Use and direct Land Use Change Emissions*

Land use and direct land use change (dLUC) emissions were determined from the NIR (Commonwealth of Australia, 2018) for Australian crop land over the period 1990-2016. Emissions from crop land prior to 1980 were determined using a linear hindcasting method. Emissions for the 2020 time period were forecast from NIR data during the period 2010-2016.

2.1.3 *Handling multi-functionality*

The production system has multiple instances where two or more outputs arise from one production system. These instances were handled in the following way. In the feed-supply chain, economic allocation processes were used to allocate impacts between protein meals and oil products (for more detail see Wiedemann et al., 2016b). Where rendered products such as meat meal were included in the feed supply chain, the raw material from meat processing was considered a residual, and only the impacts associated with rendering the product and transporting it were attributed to pig production. Allocation was avoided in the pig-supply chain by grouping all classes of pigs sold from the farm into the reference flow of 'live weight' pork.

Manure from conventional piggeries is typically land-applied on-site to crops, or pastures grazed by beef cattle or sheep. Solid residues such as sludge and spent litter are more readily transported off-site for application on crop land. Emissions arising from land application of these residues were allocated to the industry that utilised the manure nutrients. To account for the input of manure to crop systems, it was assumed that 30% of manure nutrients were returned to the grain production system, representing <1% of cereal crop fertiliser requirements nationally, after Wiedemann et al. (2016b). Manure was included as an input to the modelled cereal crop systems used in the feed inventory.

3 Results

3.1 Trends in Australian pig production

3.1.1 Herd productivity

There have been significant productivity improvements in the Australian pork industry over the last 40 years. While sow numbers remained relatively stable over the analysis period, pigs slaughtered and total sale weight have increased substantially (see Figure 1A and B), indicating that herd productivity improvements rather than herd expansion was the main driver for increased production. These productivity improvement include increased number of pigs born alive, pigs weaned and pigs slaughtered per sow, increased average carcass weight of pigs sold (Figure 1B), increased average daily gain in growing pigs (Figure 1E) and improved herd feed conversion rates (FCR) (Figure 1B).

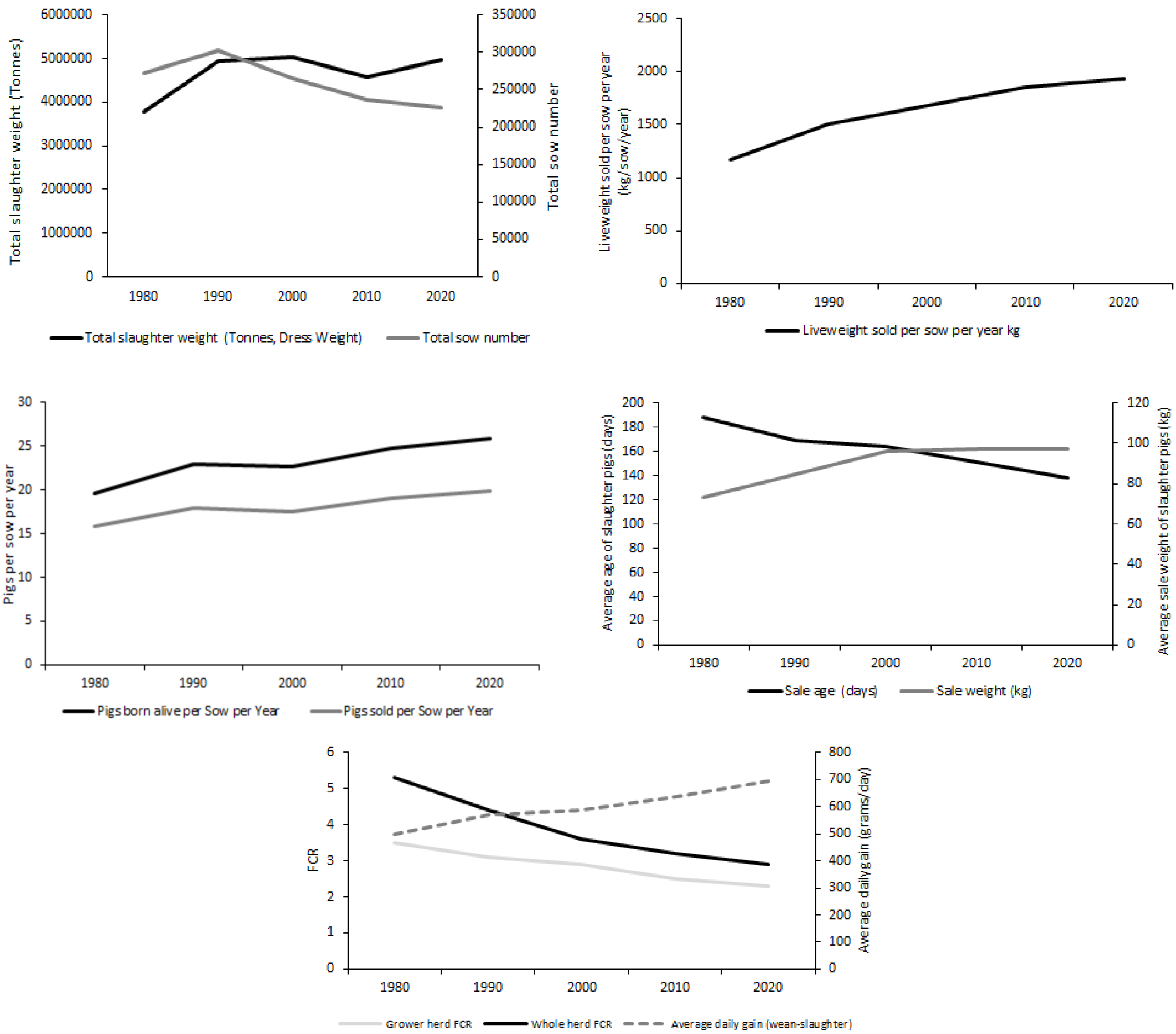


Figure 1 Herd productivity improvements in the Australian pig herd over the period 1980 to 2020

A) Total sow numbers compared to total slaughter weight (Dress Weight, DW) produced from the Australian herd,
B) Live weight sold per sow per year,
C) Pigs born alive per sow per year compared to pigs sold per sow per year,
D) Comparison of average sale age (days) to average sale weight (kg), and
E) Comparison of FCR (grower and herd) to average daily gain (wean to slaughter).

3.1.2 Housing and manure management systems

Conventional housing represented approximately 95% of all pig housing in the 1980s and 1990s, however this reduced to approximately 70% following the introduction of deep litter housing in the late 1990s. Although there was a small decrease in the 1990, outdoor housing as remained fairly constant over the analysis period, accounting for 5% of the industry housing. The conventional housing MMS has changed significantly over study period. Short HRT systems, which were more common with smaller piggeries, were used to a greater extent in 1980 (9.4%) but declined in following years, possibly reflecting the growing proportion of pigs produced in larger piggeries. Solid separation peaked in the 1990s, but declined after this. The use of uncovered anaerobic ponds peaked in the 1990s and has been steadily decreasing since, in response to the introduction of deep litter in the 2000s and more recently the introduction of anaerobic digesters and covered ponds.

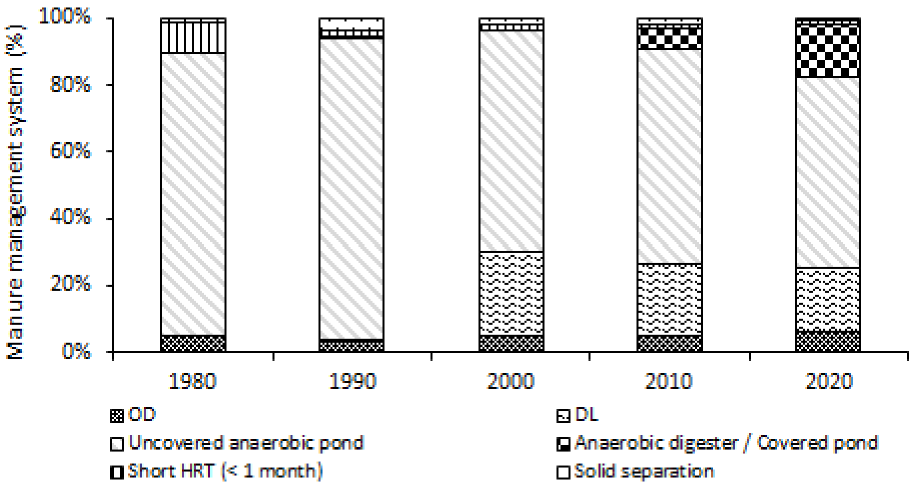


Figure 2 Changes in manure management systems over the period 1980 to 2020 for the Australian pig herd

Notes: OD: outdoor, manure directly deposited to land, DL: deep litter, uncovered anaerobic pond: conventional housing with uncovered anaerobic pond MMS, Anaerobic digester / Covered pond: conventional housing with anaerobic digester / covered pond MMS, Short HRT: conventional housing with short hydraulic retention time MMS, SS: conventional housing with solid separation MMS).

3.1.3 Trends in environmental impacts and resource use

3.1.3.1 GHG emissions

The analysis revealed a 69% decline in GHG emissions (excl. LU and dLUC), from 10.6 kg CO2-e kg LW-1 in 1980, to a projected 3.3 kg CO2-e kg LW-1 in 2020 (Figure 3). Emissions from the MMS were the largest emission source, ranging from slightly over 67% of total impacts in 1980 and 1990, to around 57% in both 2010 and 2020. Emissions from the MMS declined in absolute and proportional terms over the analysis period, reflecting the change to lower emission intensity systems such as deep litter (DL) and anaerobic digesters or covered ponds and in response to reduced flows of manure and feed waste to the MMS per kg of pork. Feed production contributed slightly over 25% of GHG emissions in both1980 and 1990, which increased to 30% in both 2010 and 2020. Impacts from services and enteric emission sources both decreased over the analysis period in absolute terms because of herd efficiency improvements and reductions in energy use for services. These sources slightly increased proportionally because of the larger declines in other emission sources. Emissions from LU and dLUC declined 89%, from 2.94 kg CO2-e kg LW-1 in 1980 to a projected 0.32 kg CO2-e kg LW-1 in 2020, principally because of the change from tillage to zero tillage in grain production systems.

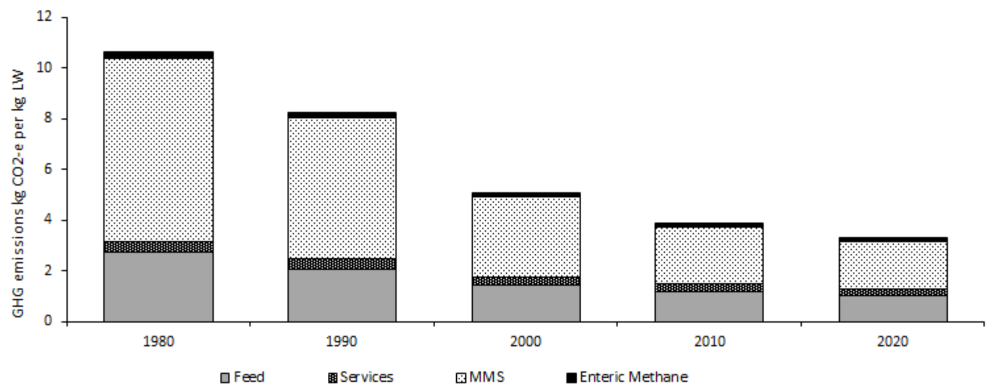


Figure 3 Changes in greenhouse gases emissions (excluding LU and dLUC) from the production of 1kg of live weight pork over the period 1980 to 2020

3.1.3.2 Fossil energy use

Fossil fuel energy declined 58% over the analysis period, from 34 MJ kg LW-1 in 1980, to a projected 14 MJ kg LW-1 in 2020 (see Figure 4). Fossil fuel energy was primarily associated with feed grain production, and substantial declines in absolute fossil fuel energy were observed over the analysis period. The contribution of feed to total energy also declined from 83% of fossil fuel energy in 1980 to 77% in 2020. The contribution of services (i.e. energy used at the piggery) also decreased in absolute terms over the analysis period, but slightly increased in proportional terms, from 17% in 1980 to a projected 23% in 2020, indicating that energy efficiency improvements were less pronounced in piggeries than in grain production systems.

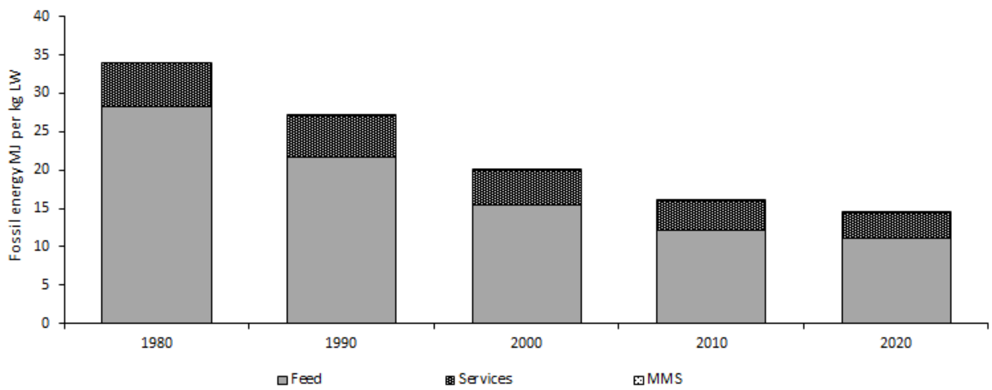
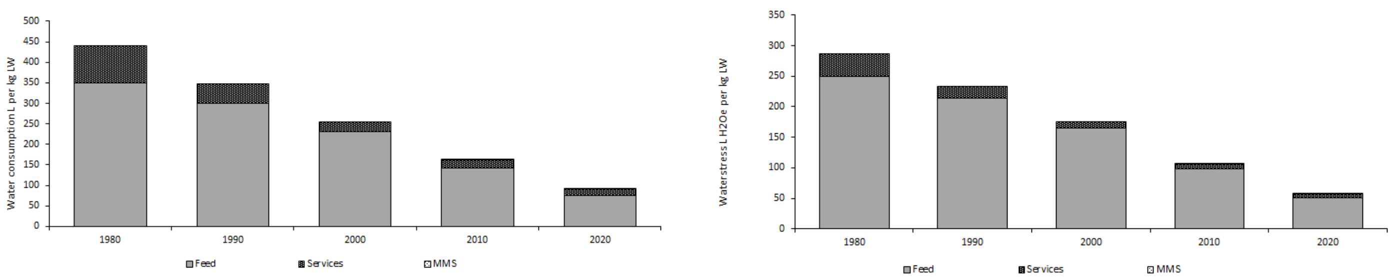


Figure 4 Changes in fossil energy use from the production of 1kg of live weight pork over the period 1980 to 2020

3.1.3.3 Fresh water consumption and water stress

Fresh water consumption was 441 L kg LW-1 in 1980, declining to a projected 90 L kg LW-1 in 2020, representing an 80% reduction in water consumption over the analysis period (see Figure 5). Water stress followed a similar trend, decreasing by slightly over 80%, from 287 L H2O-e LW-1 in 1980 to a projected 57 L H2O-e LW-1 in 2020. Irrigation associated with feed production was the single largest source of fresh water consumption, contributing over 79% in 1980, peaking at 90% in 2000, then decreasing to a projected 83% in 2020. The contribution of piggery water consumption slightly decreased from 21% in 1980 to a projected 17% in 2020.



A B

Figure 5 Changes in water consumption (A) and water stress (B) from the production of 1kg live weight pork over the period 1980 to 2020

3.1.3.4 Land occupation

Land occupation declined 63%, from 31 m2 LW-1 in 1980 to a projected 11 m2 LW-1 in 2020 (see Figure 6) in response to reductions in feed requirements (i.e. improved FCR) and increased grain yields in the feed grain production system. Interestingly, land occupation increased slightly in 2010 compared to 2000, because of the lower yields reported in these drought years (BoM, 2015).

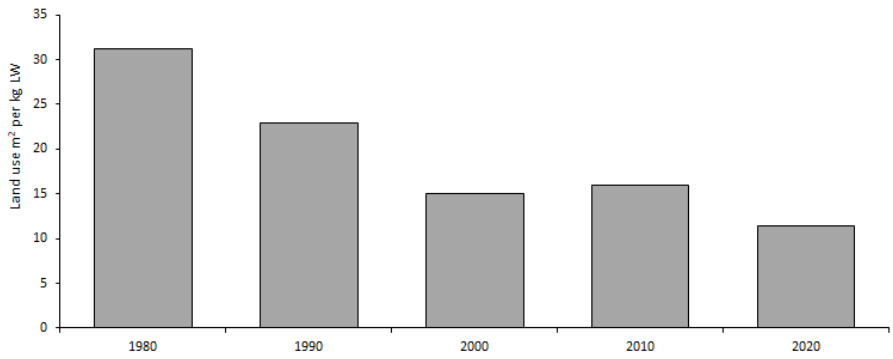


Figure 6 Changes in land use from the production of 1kg live weight pork over the period 1980 to 2020

4 Discussion

Environmental impacts and resource use associated with Australian pork production has declined substantially since 1980, in response to a range of changes in the pork production system and in grain production. Over this time, improvements in pig breeding and management have resulted in substantial improvements in production efficiency, which has led to a decrease in both upstream impacts associated with grain production, and downstream impacts associated with manure management. Changes in housing and MMS have also resulted in lower impacts over time, and improvements in the grain production system have also led to reduced impacts. These influences are described in the following sections.

4.1 The influence of changes in herd productivity

During the analysis period, pork production per breeding sow increased 55%, in response to a 39% increase in pigs sold per sow and a 26% increase in the average liveweight of pigs at slaughter. In addition, average daily gain increased 39%, resulting in faster turnoff. These changes contributed to substantial reductions in herd FCR. Herd productivity improvements are a combination of genetic gains, improved nutrition and improved husbandry. Genetic improvement is a major factor contributing to the productivity of the pork production systems, including gains in pig per litter, FCR, average daily gain (ADG), protein deposition and lean-meat content (Hermesch, 2004). Historically, genetic improvement was attained using on-farm small-scale performance testing using a selection index. Since the 1980s, boar test stations accelerated the spread of genetic improvements through the industry (NSW DPI, 2006, McLaren, 2007). In more recent years, large pig breeding companies have accelerated the rate of improvement though the application of technology to identify molecular markers for genetic improvement (Bunter and Hermesch, 2017). MacLeod et al. (2013), Garnett (2011), Fry and Kingston (2009) and Piot-Lepetit and Le Moing (2007), found that increases in pig productivity resulted in a significant decline in GHG emissions. Furthermore, several international studies on different animal production systems have shown that increasing animal productivity significantly reduced GHG emission intensity (Ripoll-Bosch et al., 2013, Gerber et al., 2011, Wall et al., 2010, Garnett, 2011, DPIRD WA, 2018) in agreeance with trends found by this study.

Increased growth rates from birth to slaughter and increased live weight at slaughter were a substantial contributor to reduced GHG emissions per kilogram of pork produced, which was similar to the trend observed in Canadian pork production (Verge et al. 2009), and for Australian beef cattle by Wiedemann et al. (2015).

In parallel to genetic improvements, pig nutrition has advanced to deliver better growth rates and lower FCR. These improvements include phase feeding, nutrient optimisation, digestibility improvements, use of enzymes and synthetic amino acids (SAA) (Radcliffe, 1987, Gardner et al., 1990, QLD DAF, 2013). Phase feeding changes the diet composition according to nutritional needs at different growth stages, and was introduced in Australia in the late 1990s (Gardner et al., 1990). Particularly, diet protein content is optimised between growth stages in order to avoid protein over-consumption and to maximise lean growth. This is particularly important to maximise lean growth potential in modern genetically improved, high lean genotypes pigs (Coffey et al., 2017). Combined with increased use of SSA, the overall dietary crude protein (CP) was observed to decrease by 14.2% between 1980 and 2020, which in turn resulted in lower nitrogen excretion and therefore lower manure related nitrous oxide emissions. The relationship between dietary CP and reduced

GHG has been shown by a number of studies (Seradj et al., 2018, Canh et al., 1998, Zervas and Zijlstra, 2002, Le et al., 2008, Sajeev et al., 2018, Kaufmann, 2015).

The increased use of SSA in pig diets has also enabled diet formulations with lower proportions of protein meal and higher levels of cereal grains. Over the analysis period, protein meal declined from 22% of the diet in 1980 to a projected 16% in 2020, which was consistent with dietary trends in other studies (Denton et al., 2005, Vergé et al., 2009). Australian cereal grains typically have relatively low emission intensities (i.e. Brock et al. 2013) while protein meals are more emission intensive, particularly in the case of imported soymeal and animal protein meals. Thus, these changes in the proportion of different commodities has contributed to lower impact diet formulations.

In the present study, diet digestibility was found to increase by 9.5% between 1980 and 2020, due to changes in the composition of diets, feed processing and the use of enzymes. Feed processing changes including the optimisation of diet particle sizes, and use of pelleted diets, have also improved digestibility and feed efficiency (Fan et al., 2017, Bao et al., 2016, Wondra et al., 1995, Goodband et al., 1995, Owsley et al., 1981). Improved digestibility is a likely contributor to the higher reported growth rates and improved feed efficiency in the herd over the analysis period, and also led to lower predicted manure excretion rates and subsequent GHG emissions from the MMS.

In addition to improvements in feed formulation, feeding systems also improved over the analysis period, resulting in a decline in feed wastage. Feed wastage in piggeries can be a substantial loss and is difficult to measure directly. Consequently, herd FCR is usually measured on the amount of feed offered to the pigs, which includes the feed consumed and the feed wasted. Over the analysis period, feed waste declined 62%, in response to better feed management and feeding systems. The major changes identified were a shift from feed type (changing from mash to pellets or liquid food), feed presentation (floor fed to non-floor feeding), and feed processing (optimising feed particle size for pig stages) (Roese, 1990, Taylor and Clark, 1990, Willis, 1999). This contributed to lower FCRs, and also reduced the amount of volatile solids lost to the MMS directly from wasted feed. Volatile solids from feed waste have been shown to contribute substantially to MMS GHG emissions (Wiedemann et al., 2016b, Manyi-Loh et al., 2013) and this trend was a contributing factor to lower MMS emissions.

These improvements in herd productivity, feed formulation and feed waste resulted in an estimated 55% decline in FCR over the analysis period. In their analysis of case study piggeries, Wiedemann et al. (2016b) found that FCR explained 88% of the variability in GHG between conventional piggeries, because of the dual impact on feed requirements and upstream impacts, and manure production, leading to lower MMS emissions. Results of this study indicate that improved FCR is the single most important factor contributing to reduction of multiple impacts from pork production over time.

4.2 The influence of housing and MMS changes

Differences in housing and MMS can have a significant effect on GHG emissions from pork production (Wiedemann et al., 2016b, Philippe and Nicks, 2015, Dennehy et al., 2017, Cherubini et al., 2015, Rigolot et al., 2010, Amon et al., 2006). Over the analysis period, changes were observed in both the housing type and the MMS used in the Australian herd, leading to reductions in GHG emissions and some reductions in piggery water use. the MMS was the largest contributor to GHG emissions, and consequently the change in GHG was most apparent. As shown by Wiedemann et al.

(2016b), use of deep litter housing for the wean-finish stage resulted in 30%, 16% and 28% reduction in GHG emissions, energy and water respectively, compared to conventional housing with uncovered, anaerobic ponds. Thus, the increase in DL housing in preference for conventional housing with uncovered anaerobic ponds was one factor leading to lower GHG emissions and to a lesser extent, lower energy and water use from services.

During the last decade, the proportion of piggeries with covered anaerobic ponds or digesters was predicted to increase from 0% to 16%, leading to further reductions in GHG emissions and energy demand. The NIR (2015) and Skerman (2017) showed a similar increase the proportion of piggeries with covered anaerobic ponds or digesters. In comparative terms, Wiedemann et al. (2016b, 2017) showed that installing a covered pond with a combined heat and power (CHP) unit reduced GHG emissions by 60% and energy demand to negligible levels for the piggery, though energy associated with upstream processes such as grain production was unchanged. Thus, the trend towards higher proportions of the industry utilising covered ponds or digesters is an important, recent trend that has led to lower environmental impacts.

Several international studies have shown that the adoption of biogas can significantly reduce the GHG emission intensity of pork production, in agreeance with trends found by this study. Lamnatou et al. (2016) showed that manure use for energy production by means of biogas generation can significantly reduce the GHG and environmental impacts of pork production, while the Cherubini et al. (2015) study demonstrated that the implementation of a bio-digestor for energy purposes had the best environmental performance for almost all the environmental impacts, mainly due to the biogas capture and the potential of energy saved.

Over the analysis period, energy demand for operating the piggery (piggery services) declined by 42%. This was in response to energy efficiency improvements and the increase in deep litter housing, combined with herd productivity improvements that resulted in shorter residence times and reduced housing requirements per kilogram of pork produced from the system.

Piggery services water requirements were also observed to decline over the analysis period, principally because of an increase in water recycling (for flushing) in conventional piggeries and the optimisation of water management via improved drinker management, optimisation of water pressure and better housing temperature management which has led to reduced water wastage (Alvarez-Rodriguez et al., 2013, Brumm et al., 2000, Brumm, 2006, Brumm, 2010).

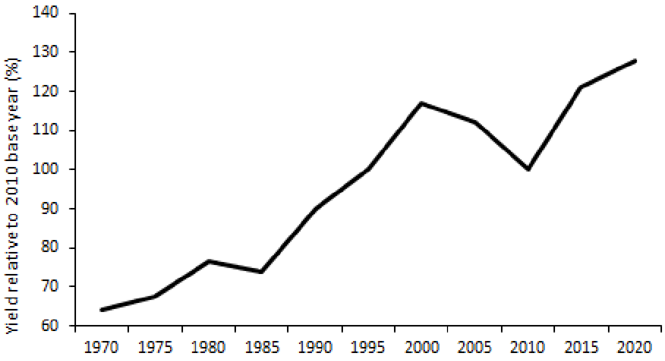
4.3 The influence of feed production changes

Feed impacts arise from field operations, fertiliser emissions, transport and milling and are typically a major impact area for pork production (Pirlo et al., 2016, Reckmann et al., 2013). The investigation of trends in the environmental impacts of diets revealed substantial reductions in all impact categories across the analysis period. These changes were largely in response to increased yields, improved tillage systems and increased efficiency in machinery operations, and a decline in the relative contribution of irrigated grain to total grain production. The combined impact of these changes was as 30% and 28% decrease in GHG emissions and fossil fuel energy demand per tonne of pig feed from 1980 and 2010. Over the same period, fresh water consumption and water stress was found to decrease by 63% and 61% per tonne of pig feed, while land occupation declined by 34%. This period corresponded to a substantial 40% yield increase for Australian broadacre crops and

90% and 16% reduction in tillage events and machinery fuel use respectively (see Figure 3a), though fluctuations were observed in response to drought conditions around the year 2010 (ABS, 2012b). The uptake of zero tillage was a notable change during this period, and has been identified as one of the most significant changes in agricultural practices over the last 40 years in Australia (Barson et al., 2012). This has resulting in reduced fuel requirements and reduced land use (soil) carbon losses. Concurrently, machinery size has increased, resulting in greater fuel use efficiency for field operations. These combined effects have led to lower environmental impacts from Australian grain production and better soil condition in crop lands. Changes in GHG and energy were less pronounced when projected to 2020, largely because the uptake of zero tillage slowed (see Figure 7B) as it reached very high uptake levels, leaving little room for further improvement. Additionally, yield increases were accompanied by higher fertiliser and herbicide usage, resulting in little improvement in GHG or energy demand per tonne of feed over this period (see Supporting Information, section: Feed Production Data). In contrast to this, the increase in yield resulted in further declines in land occupation of a projected 18% over this decade.

Changes in fresh water consumption over the analysis period were driven by different trends compared to GHG, energy and land occupation. Fresh water consumption was largely associated with the irrigated fraction of the total cereal crop, which contributed a disproportionally large amount of total water. The irrigated broadacre crop share of the market, by estimated tonnage, has reduced by 42.9% between 1980 and 2020.

The application rate of water per hectare also reduced by 41.6% during this period due to an increase in water price and improvements in irrigation system efficiency. This resulted in a market dilution effect leading to lower irrigation water relative to total grain production. As a result of these two changes, the average irrigation water use per tonne of Australian broadacre crop on the market reduced by 65%. This is illustrated in Figure 7c, which shows the proportion crop yield from irrigated cereal grain over the analysis period. The contribution of irrigated crops was found to peak in the 1990s, then to decline steadily, with further declines projected to 2020 in response to ongoing declines in irrigation water use for cereal grains (ABS, 2017).



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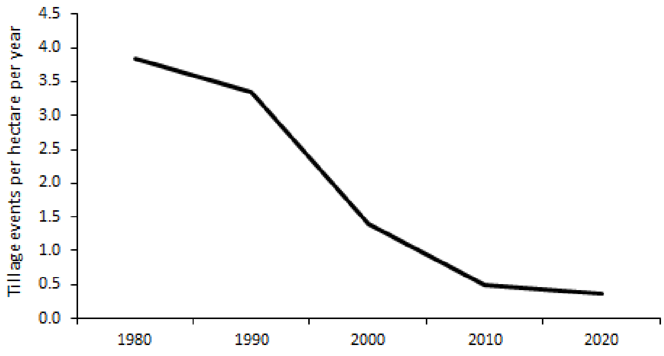

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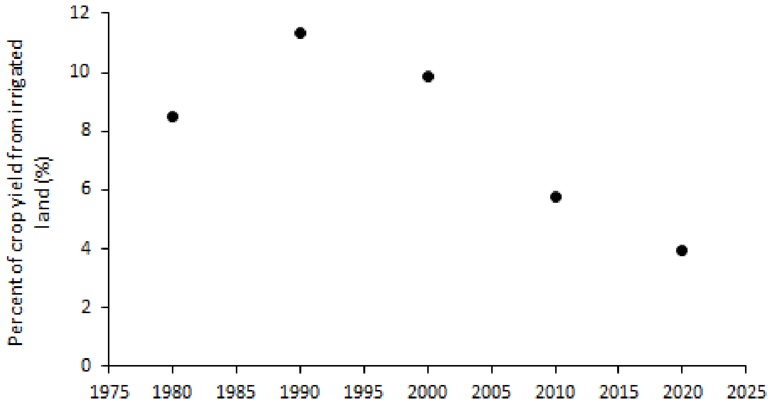

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Figure 7 Changes in grain production systems over the period 1980 to 2020

A) Historical Australian cereal grains (wheat, barley and maize) yield relative to 2010 base year in 5-year increments from 1970-2020 (ABS, 2012),

B) Historical Australian crop tillage events per hectate per years (ABS, 2018a), and

C) Percentage of Australian crop yield from irrigated crop land (including supply losses) (ABS, 1999-2017), data from 2015-17 was used to predict irrigation values for 2020

4.4 Comparison with literature

Vergé et al (2009) compared Canadian pork production from 1981 to 2001 and showed that the GHG emission intensity (excluding LU and dLUC) decreased by 30% over this period, from 2.99 to 2.31 kg CO2-e kg LW-1. The decline in emissions was attributed to higher diet digestibility, lower N-fertiliser use in crop systems as well as improved breeds and changes in management practices which resulted in improved herd productivity. Similarly, Boyd et al (2012) reported a decline in GHG emission intensity for USA pork from 3.8 to 2.5 kg CO2-e kg-1 carcase weight (excluding LU and dLUC) from 1959 to 2009. This was attributed to a reduction in pesticide and fertiliser use in crop systems, changes in MMS, and improvement in production efficiency for both pig production and crop yields.

Interestingly, the change in emission intensity in the present study was much greater than reported in the north American studies. This can be partly explained by the higher historic MMS emissions in Australia, where uncovered anerobic ponds are prevalent and emission rates are very high in comparison to northern hemisphere countries (McGahan et al. 2016), leading to higher emission intensities. It was also clear that the reported improvement in productivity was greater in the present study, partly because Australian pig production had poorer rates of productivity in the early part of the analysis period. Boyd et al (2012) also reported the change in fresh water consumption in piggeries, which was found to decline from 30 L kg of LW-1 in 1959 to 18 L kg of LW-1 in 2009, a 41% improvement. The authors postulated that reduced water consumption was the result of herd productivity improvements. The present study reported a change in pig water consumption from 90 to 15 L kg of LW-1, with the larger change principally in response to increased water recycling in Australian piggeries, and the increased proportion of deep litter housing together with herd productivity improvements. In contrast to the present study where irrigation water use decreased by 66% over the analysis period, Boyd et al (2012) reported a 6-fold increase is water use for crop irrigation in 2009 compared to 1959, highlighting differences in water management in the two countries. In Australia, irrigation water has become increasingly constrained, and the introduction of water markets (National Water Commission, 2011) has led to water being utilised in the highest value crops, potentially reducing water availability for cereal grain production. The reduction in water for Australian pork production was similar in magnitude to the change in water use for Australian beef (Wiedemann et al. 2015) with some similar drivers (reduced irrigation water use) but also some differences. In the beef study, water use declined substantially in response to changes in losses from artesian bore water, which was not a feature in the pork study.

Emissions were also found to decline by 14% for Australian beef between 1981-2010 (Wiedemann et al. 2015) in response to efficiency gains through heavier slaughter weights, increases in growth rates and improved survival rates. This was substantially less than the reduced emissions for pork, because the productivity improvements for beef have been less pronounced, and emission sources in beef (i.e. enteric methane) are more difficult to control. One contrasting result in the beef study of Wiedemann et al. (2015) was the increase in energy associated with beef production, following intensification. This trend was reversed in pig production, though energy intensity remained higher than for beef cattle, where inputs associated with feed and farm operations are low compared to pork production.

4.5 Implications to the Australian pork industry

The pork industry, like all industries, must continue to improve efficiency and reduce environmental impacts to remain competitive and contribute to better sustainability outcomes for food production. While this study revealed a considerable decline across all impact categories, it was also evident that the rate of improvement in GHG emission intensity and energy demand slowed substantially in the last decade. Additionally, while complementary reductions in environmental impacts occurred in grain production systems for the first three decades, there was no reduction in GHG or energy projected between 2010 and 2020, because technology changes had been implemented, and fertiliser inputs increased (see supplementary materials). In contrast, further reductions in fresh water consumption were observed in the feed production system across the whole time period and could continue as water is transferred to higher value users. The declining rate of improvement indicates that targeted initiatives will be required to make further substantial changes in GHG, energy and fresh water consumption. The largest opportunities exist in further herd productivity improvements, optimised diets and increased utilisation of waste feed sources, increased uptake of biogas, improved utilisation of effluent water and nutrients, and potentially utilisation of other forms of renewable energy.

4.5.1 Herd productivity improvements

While Australian pig herd performance has significantly improved since the 1980s, it is still behind world leaders Demark, the Netherlands, Canada and USA, indicating there is still room for herd performance gains from genetic improvements (Pork CRC, 2017). Genetic improvements in growth, reproduction and carcass traits as well a focus on genotype and commercial environment interactions could optimise the resource use of pork production, further reducing the emission intensity of piggery operations (McLaren, 2007).

Increasing the turnoff weight at slaughter is an alternative which could substantially reduce the environmental footprint of piggery operations. The authors previously used consequential life cycle assessment to incorporate the market effects (supply, demand and price) and predict the impact of future pork production in Australia (Wiedemann and Watson, 2018). Consequential life cycle assessment enables the consequences of changing market (i.e. increase or decrease pork production) to be investigated. When consequential LCA is used in conjunction with attributional LCA (like this paper), it allows for the comprehensive assessment of the impacts from additional pork (consequential LCA) to the average pork (attributional LCA). Wiedemann and Watson (2018) found increasing the turnoff weight by 10 kg LW (to an average of 110 kg LW) in an increasing pork market would lower GHG emission per kg of LW produced due to reduced feed requirements. That is, increasing turn off weight of the additional pigs needed to meet increased market demand would have a lower GHG emission intensity. The emission from additional pork is significantly lower than the impacts from average pork. Likewise, an Australian beef GHG study showed that that imposing more mitigation strategies with the potential to profitably enhance liveweight turnoff allowed a greater reduction in emissions intensity (Harrison et al., 2016).

4.5.2 Optimised diets

The optimisation of pig diets by increasing the digestibility could reduce total feed consumption and nutrient excretion, which could further reduce the environmental footprint of piggery operations in Australia. Additionally, reducing feed wastage, through improved feeder types and management practices is an optimisation strategy that will increase feed efficiency (Schell et al., 2001, Carr, 2008, DeRouchey and Richert, 2010) and reduce the GHG emission associated with manure treatment in uncovered anaerobic ponds. Another common optimisation strategy is reducing dietary crude protein in pig rations by increasing the inclusion rates of SAAs, reducing the proportion of high protein ingredients in feed and reducing environmental impacts (Meul et al., 2012, Garcia-Launay et al., 2014, Ogino et al., 2013).

Additionally, the use of local diet components can significantly reduce the GHG and fossil fuel emissions from feed. For example, one strategy to reduce GHG and dLUC emissions from imported soybean meal would be to increase alternative local protein crops production, though this would need to be achieved without inducing an expansion of crop land and subsequent dLUC emissions in Australia (Wiedemann and Watson, 2018). Noya et al. (2017) showed the use of ingredients cultivated in regions close to the location of pig production reduced the environmental burdens of pig feed production. Furthermore, Lamnatou et al. (2016) showed that pig diets formulated with higher levels of crops with lower cultivation impacts, use of sustainable agricultural practices and local production of the feed components can significantly reduce the environmental impacts of pork production. Analysis of the Brazilian pork industry found that avoiding the use of grain from deforested areas can significantly decrease the environmental impacts of pork production (Cherubini et al., 2015).

Of note is the utilisation of food rejected from the human supply chain pre-consumption to reduce GHG emissions. Approximately 40% of food in the Australian human supply chain is wasted (FAO, 2013; Gustavsson et al., 2011; Lapidge, 2015), representing some 22 M GJ of food energy (equivalent to 1.23 M tonnes of cereal grain) that is potentially available in Australia annually. According to Wiedemann (2018) with full energy recovery, this corresponds to 78% of the feed requirements for the Australian pig industry. While there are logistical and regulatory barriers (swill feeding) associated with human supply chain pre-consumption food waste, this indicates that there is significant potential for the pig industry to continue to reduce impacts associated with feed inputs, with associated economic benefits also.

4.5.3 Optimised biogas

Increased uptake of biogas and closed loop technologies is a major opportunity for improved environmental outcomes for the pig industry. Wiedemann and Watson (2018) found that biogas production was a common feature of the larger, new conventional piggery developments in Australia, however biogas production was not cost effective in small and medium piggeries, limiting uptake. With increased biogas uptake, MMS emissions and on-farm energy emissions will continue to decline in the Australian industry.

4.6 Limitations

An important limitation of this work is that 1980 and 2020 data was produced from projected trends. Prediction of future impacts is complicated by the requirement to project industry changes over a certain time horizon. In the present study, a model was constructed that aimed to represent a complex market and production dynamic in 2020.fSI While, the results do not describe the full environmental consequences of future production, it revealed that environmental efficiency is improving. Water improvements gains were estimated from expert opinion, so there is higher uncertainty associated with water values. Additionally, this report was not comprehensively assessing all nutrient emissions associated with pork production. It should also be noted that at the time of project inception the economics of pork production were significantly better than at the time of writing. While Australian consumption of pork is still increasing, and new piggery developments will be needed to meet this demand, the lower prices may affect the scheduling of new developments. Thus, as the developments are likely to be delayed, the improvements projected in this study may be less than projected.

5 Implications & Recommendations

5.1 Conclusions

The Australian pig industry has experienced significant changes in the scale and level of productivity achieved by producers over the last four decades. There has been a significant improvement in productivity, with more liveweight sold per sow, and lower FCRs. Estimates of improvements in environmental efficiency reflected enhanced herd productivity and changes in management of key resources such as water and land. Over the four decades since 1980 there has been a 69%, 58%, 80% and 63% reduction in GHG emissions, fossil fuel use, water consumption and land occupation, respectively. It also highlights that there has been some slowing of the rate of improvement since 2010 despite the potential for further productivity improvements. This study represents the most comprehensive analysis to date of trends in the environmental impacts of Australian pork production on a national scale. Improved herd and system efficiency led to improved feed conversion ratio, resulting in lower feed requirements, and reduced manure production, which had a disproportionally larger effect on reducing manure GHG emissions. The introduction of deep litter housing and covered ponds in Australian piggeries contributed to reducing environmental impacts. Concurrently, reduced tillage, higher yields and a decrease in the proportion of irrigation water used for grain production improved the efficiency of the feed grain production systems resulting in lower impacts per kilogram of feed grain produced.

5.2 Recommendations

A series of recommendations have been developed following this work, relating to future research, development and communication.

5.2.1 Research and Development

Reducing environmental impacts is an industry priority. This research points to the following key areas for future research and development:

- *Biogas and closed loop technologies*. These are well recognised by industry as an important means of reducing impacts from GHG, energy, water and nutrients. The increased implementation of capped aerobic ponds for energy can significantly decrease the environmental impacts of pork. Ongoing policy support is required to maximise uptake, particularly among smaller producers and those with lower cost power supplies. Closed loop technologies are also a priority, to improve utilisation of water and nutrients from piggeries.

- *Utilisation of food waste*. In Australia there are large quantities of waste food from the human food supply chain that could be used to reduce the environmental impacts of feed and to reduce the costs of feed inputs. While well understood and known by industry, there would be much greater opportunity for uptake if known barriers could be overcome. Investigating the potential to utilise waste heat from biogas operations to heat treat some forms of food waste could further reduce reliance on expensive and high environmental impact feed ingredients such as protein meals. It is also possible that utilising food waste diverts these products from land fill, further reducing emissions. This is an area where further work is needed.

- *Development of "sustainable diets" and optimised feed formulations*. The use of local and/or sustainable diet components can significantly reduce the GHG and fossil fuel emissions from feed. In particular, options continuing to decrease reliance on imported soymeal is a priority to decrease environmental impacts from feed. There may also be ongoing opportunities to reduce crude protein levels and decrease nitrogen related manure emissions. This research area could benefit from cross-industry investment from monogastric species to investigate the opportunity for environmentally optimised diets.

- *Nutrient recovery and improved effluent / manure utilisation*. Manure and effluent nutrients could be utilised to a higher extent to offset fertiliser requirements in crops and pastures. An audit or survey of current manure and effluent management would provide valuable information to determine if further research, extension or development is required to improve manure and effluent nutrient utilisation by industry. There are opportunities to reduce reported impacts from pork by substituting manure for synthetic fertilisers, but currently the estimated proportion of manure used in a beneficial way is relatively low and new information would be beneficial.

- *Investigating optimised "future pork" systems*. The partner study to this report commissioned by the Pork CRC (Wiedemann & Watson 2018) conducted a preliminary study of opportunities for reduced emission pork production. This important new avenue of research is required to demonstrate that future pork production will have lower impacts than current industry averages, because of substantial improvements in environmental performance among the top industry performers. Further research and development of communication strategies in this area would be beneficial.

- *Carbon Neutral pork*. Environmental impacts have been shown to decline over time in this study, and the opportunity now exists to develop verified carbon neutral pork based on similar analysis approaches as applied here. This is an opportunity the industry would benefit from exploring, to determine the methods, requirements and costs for verified carbon neutral pork.

- *Assessment of change in nutrient emissions*. This study, and previous LCAs, have excluded nutrient impacts despite this being an important area of environmental impact for pork production. New methods have now been assessed to report nutrient impact intensity (kg nutrient per kg pork) and this would be a highly valuable area of research to provide both a rounded view of environmental impacts, and also to demonstrate to regulators that intensive pork production has low impacts relative to pork production. This is an important perspective that needs to be presented using rigorous research.

5.2.2 Communications

This research has potential to provide a valuable basis for consumer and government communications, both as a means of communicating the achievements made by industry, and also as a way of developing support for further advancements. To underpin public communications, the

results would receive more recognition and be more defensible if the work was published in a peer reviewed journal literature. to peer reviewed publication.
Additional communication tools such as fact sheets and infographics would be beneficial for simplifying and communicating the message to a non-technical audience.

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7 Appendix 1 – Supporting Information

Please note that the Appendix has been modified to a journal format and is referred to as "Supporting Information" (SI) in text.

7.1 Herd inventory data

Liveweight was determined by adjusting the total tonnes of dressed weight pork produced to liveweight with dressing percentages. Namely, as porkers have a poorer dressing percentage compared to finishers, the dressing percentage was altered by 0.5% between decades from 74.5% in 1980 to 76.5% in 2020 to reflect the higher proportion of porkers historically. Liveweight sold per sow per year was determined by first adjusting the total tonnes of dressed weight pork produced to liveweight, then dividing by total sow numbers (ABS, 1999-2018). Average sale weight of finisher pigs was determined by first adjusting the total tonnes of dressed weight pork produced to liveweight, then dividing by the total slaughter pig numbers (ABS, 2017). The average age of finisher pigs was determined by subtracting birth weight (1.4kg) from the average sale weight of finisher pigs, then dividing by the average daily gain (estimated using PigBal, Skerman et al., 2015). Tables 6 to 10.

Table 6 1980 Australian pig herd performance data and data sources

Category	Units	1980	Notes	Reference
Weaning age	**days**	34.3	Average	Pig Journal Vol 4: Are traditional creep diets costing you to much?
Litters per sow per year	**#**	2.1	Average	Pig Journal Vol 4: Victorian Producers suffer reduced profit margins Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Pig Journal Vol 8 (1985): Tom uses liquid feeding to improve feed conversion and productivity McErlane Vol 12(9) Rags to riches shows there is still room for family business Lean, A. Jul (9) AIMS figures show cost benefits from the proper use of computer bureau service. Paton, D. (1987) NSW herd performance not very impressive Paton, D. (1987) NSW herd performance not very impressive Crawlord, J. (1982) How and why a Cowra couple are building a new piggery Curtis, F. (1983) Pilot study shows larger herds profit
Pigs born alive per Sow per Year	**#**	19.6	Average	Pig Journal Vol 4: Victorian Producers suffer reduced profit margins Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency
Pigs weaned per Sow per Year	**#**	14.7	Average	Pig Journal Vol 4: Victorian Producers suffer reduced profit margins Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency

				Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Lean, A. Jul (9) AIMS figures show cost benefits from the proper use of computer bureau service. Curtis, F. (1983) Pilot study shows larger herds profit Barker, I. (1980) No reason why we cannot produce 14-16 piglet/sow/year with a little more effort
Pigs sold per Sow per Year	**#**	13.9	Calculation	ABS (2017) Slaughter numbers divided by ABS (1999-2018) sow numbers
Liveweight sold per sow per year	**kg**	1022.4	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (1999-2018) sow numbers.
Average sale weight of finisher pigs	**kg**	75	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers.
Average age of finisher pigs	**days**	144	Calculation	(Average sale weight- birth weight)/ ADG ((ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers) – 1.4 kg)/ PigBal 4 (Skerman et al., 2015) estimation ADG
Average daily gain (wean-finisher slaughter)	**gram/day**	500	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (grower herd)	**FCR**	3.5	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (whole herd)	**FCR**	5..2	Average	Barker, I. (1980) No reason why we cannot produce 14-16 piglet/sow/year with a little more effort Curtis, F. (1983) Pilot study shows larger herds profit Sloane, J. (1982) Piggery performance analysis now available to Queensland producers. Cutler and Treacy vol 12 (10) Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Pig Journal Vol 4: Victorian Producers suffer reduced profit margins
Pigs weaned per Sow per Year	**#**	14.7	Average	Pig Journal Vol 4: Victorian Producers suffer reduced profit margins Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Lean, A. Jul (9) AIMS figures show cost benefits from the proper use of computer bureau service. Curtis, F. (1983) Pilot study shows larger herds profit Barker, I. (1980) No reason why we cannot produce 14-16 piglet/sow/year with a little more effort
Pigs sold per Sow per Year	**#**	13.9	Calculation	ABS (2017) Slaughter numbers divided by ABS (1999-2018) sow numbers
Liveweight sold per sow per year	**kg**	1022.4	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (1999-2018) sow numbers.
Average sale weight of finisher	**kg**	75	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers.

pigs				
Average age of finisher pigs	**days**	144	Calculation	(Average sale weight- birth weight)/ ADG ((ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers) – 1.4 kg)/ PigBal 4 (Skerman et al., 2015) estimation ADG
Average daily gain (wean-finisher slaughter)	**gram/day**	500	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (grower herd)	**FCR**	3.5	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (whole herd)	**FCR**	5..2	Average	Barker, I. (1980) No reason why we cannot produce 14-16 piglet/sow/year with a little more effort Curtis, F. (1983) Pilot study shows larger herds profit Sloane, J. (1982) Piggery performance analysis now available to Queensland producers. Cutler and Treacy vol 12 (10) Pig Journal Vol 7 (1984): Producer support helps independent feed mill to improve efficiency Pig Journal Vol 4: Victorian Producers suffer reduced profit margins

Table 7 1990 Australian pig herd performance data and data sources

Category	Units	1990	Notes	Reference
Weaning age	**days**	24.5	Average	PigStat (1993, 1996)
Litters per sow per year	**#**	2.2	Average	PigStat (1993, 1996)
Pigs born alive per Sow per Year	**#**	22.9	Average	PigStat (1993, 1996)
Pigs weaned per Sow per Year	**#**	19.9	Average	PigStat (1993, 1996)
Pigs sold per Sow per Year	**#**	17.9	Calculation	ABS (2017) Slaughter numbers divided by ABS (1999-2018) sow numbers
Liveweight sold per sow per year	**kg**	1373.7	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (1999-2018) sow numbers.
Average sale weight of finisher pigs	**kg**	84.9	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers.
Average age of finisher pigs	**days**	146	Calculation	(Average sale weight- birth weight)/ ADG ((ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers) – 1.4 kg)/ PigBal 4 (Skerman et al., 2015) estimation ADG
Average daily gain (wean-finisher slaughter)	**gram/day**	568	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (grower herd)	**FCR**	3.1	Modelled	PigBal 4 (Skerman et al., 2015) estimation

FCR (whole herd)	FCR	4.4	Average	PigStat (1993)

Table 8 2000 Australian pig herd performance data and data sources

Category	Units	2000	Notes	Reference
Weaning age	**days**	21.0	Average	PigStat (1999, 2000)
Litters per sow per year	**#**	2.2	Average	PigStat (1999, 2000)
Pigs born alive per Sow per Year	**#**	22.6	Average	PigStat (1999, 2000)
Pigs weaned per Sow per Year	**#**	19.4	Average	PigStat (1999, 2000)
Pigs sold per Sow per Year	**#**	17.5	Calculation	ABS (2017) Slaughter numbers divided by ABS (1999-2018) sow numbers
Liveweight sold per sow per year	**kg**	1807.9	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (1999-2018) sow numbers.
Average sale weight of finisher pigs	**kg**	96.0	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers.
Average age of finisher pigs	**days**	161	Calculation	(Average sale weight- birth weight)/ ADG ((ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers) – 1.4 kg)/ PigBal 4 (Skerman et al., 2015) estimation ADG
Average daily gain (wean-finisher slaughter)	**gram/day**	586	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (grower herd)	**FCR**	2.9	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (whole herd)	**FCR**	3.6	Average	PigStat (1999, 2000)

Table 9 2010 Australian pig herd performance data and data sources

Category	Units	2010	Notes	Reference
Weaning age	**days**	23.2	Average	Australian Pig Annual (2010-2011, 2011-2012)
Litters per sow per year	**#**	2.3	Average	Australian Pig Annual (2010-2011, 2011-2012)
Pigs born alive per Sow per Year	**#**	24.8	Average	Australian Pig Annual (2010-2011, 2011-2012)
Pigs weaned per Sow per Year	**#**	21.5	Average	Australian Pig Annual (2010-2011, 2011-2012)
Pigs sold per Sow per Year	**#**	19.1	Calculation	ABS (2017) Slaughter numbers divided by ABS (1999-2018) sow numbers
Liveweight sold per sow per year	**kg**	1839.5	Calculation	ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (1999-2018) sow numbers.
Average sale weight of	**kg**	97.2	Calculation	ABS (2018) Total tonnes dressed weight

finisher pigs				produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers.
Average age of finisher pigs	**days**	150	Calculation	(Average sale weight- birth weight)/ ADG ((ABS (2018) Total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) total slaughter pig numbers) – 1.4 kg)/ PigBal 4 (Skerman et al., 2015) estimation ADG
Average daily gain (wean-finisher slaughter)	**gram/day**	636	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (grower herd)	**FCR**	2.5	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (whole herd)	**FCR**	3.2	Average	Australian Pig Annual (2010-2011, 2011-2012)

Table 10 2020 Australian pig her performance data and data sources

Category	Units	2020	Notes	Reference
Weaning age	**days**	22.3	Prediction-excel forecast	Using: Pigstat (1993, 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006) and Australian Pig Annual (2006-2008, 2009-2010, 2010-2011, 2011-2012)
Litters per sow per year	**#**	2.3	Prediction-excel forecast	Using: Pigstat (1993, 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006) and Australian Pig Annual (2006-2008, 2009-2010, 2010-2011, 2011-2012)
Pigs born alive per Sow per Year	**#**	25.8	Prediction-excel forecast	Using: Pigstat (1993, 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006) and Australian Pig Annual (2006-2008, 2009-2010, 2010-2011, 2011-2012)
Pigs weaned per Sow per Year	**#**	23.1	Prediction-excel forecast	Using: Pigstat (1993, 1996, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006) and Australian Pig Annual (2006-2008, 2009-2010, 2010-2011, 2011-2012)
Pigs sold per Sow per Year	**#**	19.9	Calculation	ABS (2017) predicted slaughter numbers divided by ABS (1999-2018) predicted sow numbers
Liveweight sold per sow per year	**Kg**	2276.3	Calculation	ABS (2018) predicted total tonnes dressed weight produced (adjusted to live weight) divided by ABS (1999-2018) predicted sow numbers.
Average sale weight of finisher pigs	**Kg**	97.2	Calculation	ABS (2018) predicted total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) predicted total slaughter pig numbers.
Average age of finisher pigs	**days**	138	Calculation	(Average sale weight- birth weight)/ ADG ((ABS (2018) predicted total tonnes dressed weight produced (adjusted to live weight) divided by ABS (2017) predicted total slaughter pig numbers) – 1.4 kg)/ PigBal 4 (Skerman et al., 2015) estimation ADG

Average daily gain (wean-finisher slaughter)	**gram/day**	693	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (grower herd)	**FCR**	2.3	Modelled	PigBal 4 (Skerman et al., 2015) estimation
FCR (whole herd)	**FCR**	2.9	Prediction	Using Australian Pig Annual (2006-2008, 2009-2010, 2010-2011, 2011-2012), Wiedemann et al., 2016; Pork CRC, 2017 and Wiedemann and Watson, 2018.

7.2 Herd productivity

At the national level, the number of pigs slaughtered, divided by the number of sows, provides an estimated number of pigs sold per sow per year, an important herd productivity parameter. Similarly, the number of pigs sold / sow provides an indication of the number of litters annually, and therefore the average age and growth rate of sale pigs. These data can therefore be used to estimate the key features of the Australian breeding herd, and this was the approach applied in the present study.

Modifications were required to determine appropriate herd characteristics from these data. Firstly, pig slaughter numbers and slaughter weights were assumed to include cull breeders from the pig breeder herd, which are processed with the finisher pigs. The first adjustment made was to remove the number of slaughtered breeder sows to provide a predicted number of slaughtered finisher pigs. The number of cull breeder sows was estimated to equal the number of gilt replacement sows less the breeder mortalities. With the average slaughter weight and dressing percentage, the age at slaughter was calculated along with the number of pig cycles/year.

For comparison with the above herd data estimation method, a wide-ranging review was undertaken of historical data sources to investigate the key parameters and the correlation between these and the estimates based on ABS. This analysis showed a systematic over-prediction in the weight of slaughter pigs in the literature compared to the national slaughter statistics, with the error being greatest in the first two decades (where representative data sources were more difficult to find). The more recent decades showed a better correlation between estimates made using ABS datasets and industry data from PigStats and APL surveys.

7.2.1 National standard diets

7.2.1.1 Diet trends

Trends data from large piggeries and consultation with long term industry nutritionists were used to determine diet trends from 1980 to 2020. The following section details the modification that were applied to the 2010 base diets.

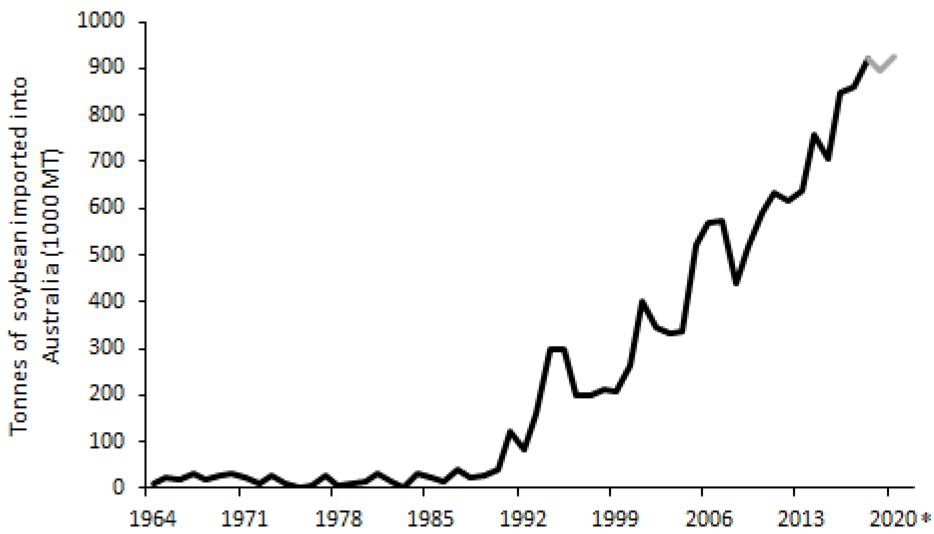
7.2.1.2 Digestibility

A large number of studies have shown particle size reduction increases the surface area of the grain, thus allowing for greater interaction with pig digestive enzymes, improving the digestibility of feed (Fan et al., 2017, Bao et al., 2016, Wondra et al., 1995, Goodband et al., 1995, Owsley et al., 1981). Additionally, in modern pig diets, enzymes are added to increase digestibility. Torres-Pitarch et al (2017) found that enzyme complexes including protease and mannanase improve nutrient digestibility. Similarly, O'Connell et al (2005), Emiola et al (2009), Patience et al (1992), Mavromichalis et al (2000), Zhang et al (2014) and Jo et al., (2012) found that enzyme supplementation can improve digestibility in pig diets.

Diet digestibly was corrected between decades to account for improvement in particle size optimisation and the inclusion of enzymes in Australian pig diets (QLD DAF, 2018, Edwards, 2014, Choct et al., 2004, Nguyen et al., 2015, I'Anson et al., 2013, NSW DPI, 2013, NSW DPI, 2014). On average, digestibility was reduced by 6%, 4% and 2% in the 1980, 1990 and 2000 respectively. The digestibility of 2010 base diets were not changed, as the digestibility in the PigBal model reflects 2010 diet digestibility values, while the digestibility of 2020 was increased by 1% to conservatively reflect the improvements in digestibility and increased use of enzymes in pig diets.

7.2.1.3 Oilseed meals

Most producers only used Australian-grown ration components in the 1980's, but in the following decades, changes in the type of protein meals used were observed. Animal protein meals were used at high rates in the early part of the study period, but declined as these were replaced with oilseed meals and synthetic amino acids. Market trends of oilseed meals (that were used in each state) were investigated, and decade diets were adjusted accordingly. The proportion of oilseed meal has increased in pig diets, replacing animal-based protein meal over the study period. The proportion of soy and canola meal were predicted from trends identified from industry reports on protein meal use (Pork CRC, 2007, Willis, 2003, Mailer, 2004 and Feed Grain Partnership, 2016) and soybean meal import volumes (Figure SI 1). Figure SI 1 shows the tonnes of soybean imported into Australia has significantly increased from 1964 to 2017, and this expansion was driven by increased demand for soymeal in pig and poultry diets. The source of imported soybeans has varied considerably from 1980 to 2010 (Table SI 1). These reports indicated the total tonnes of soy and canola meal used at different time points during the study period, enabling estimation of the percentage of these in the ration. These trends were also compared to diets accessed from large-scale commercial piggeries, and diet formulations from industry nutritionists (S. Willis pers. comm). The trend showed an increase in soymeal and canola meal over the study period.



*2020 projected by authors from historic trends

Figure SI 1 Total tonnes of soybean imported into Australia from 1964 to 2017 (Index Mundi, 2018)

Table SI 1 Tonnes of soybean imported and source in 1980, 1990, 2000, 2010, 2020 (OEC, 2018)

		Source of soybean imports (% of soybean import)			
	Tonnes imported	**USA**	**China**	**Brazil**	**Argentina**
1980 [a]	16000	61.00	36.00	0.50	0.00
1990	41000	94.00	0.00	0.62	0.00
2000	263000	13.00	0.00	86.00	0.00
2010	589000	46.00	0.00	0.28	52.00
2020 [a]	930873	0.07	0.62	2.50	96.00

[a] 1980 and 2020 soybean import countries predicted by authors from historic trends from 1990-2017

In the early 1990s canola became a major crop in Australia (Colton and Potter, 2007), with the use of canola meal increasing in pig diets. In recent years, canola meal has been used to replace soybean meal in QLD and NSW/VIC (Edwards, 2013).

The lupins and field peas pig diet component have been produced in Australia over the study period. Lupin production in WA peaked in late 1990 to early 2000 and from 2010 onwards has been stable (WA DPIRD, 2018), while the production of field peas in SA has been stable since the 1990s (Pulse Australia Limited, 2016). Table SI 2 shows the modifiers that were applied to the base diet for lupin and field pea oilseed meals based on market trends.

Table SI 2 Lupin and field pea meals diet modifiers used in study

Year	Lupins	Field peas
1980	1	0.75
1990	1.25	1
2000	1.5	1
2010	1	1
2020	1	1

7.2.1.4 Synthetic Amino Acids

The industrial application of amino acids for animal feed started in the late 1950's. The synthetic production of DL-Methionine began in the late 1950's and was used in poultry feed. The synthetic production of L-Lysine began in the 1960's (Toride, 2004). By the late 1980's DL-Methionine and L-Lysine, HCl, L-Threonine and L-Tryptophan were being produced synthetically (Toride, 2004). Initially, the cost of production was quite high which limited the application in the pig industry in the 1980's. However, with progress in biotechnology, the cost of production of synthetic amino acids has been significantly reduced. This has led to an expansion in the use of amino acids in Australian pig feed. Since the 1990's, synthetic DL-Methionine and L-Lysine have been commonly used in Australian pig diets. While synthetic Threonine and L-Tryptophan are available, their high production costs limit their application.

Australian research into the lysine requirements in finisher pigs in a commercial setting found that lysine requirement for finishing pigs of modern Australian genotypes is substantially higher than used commercially to date (Edwards et al., 2013). For optimal average daily gain, FCR, carcase gain and profitability the lysine requirement was estimated to be 0.62 to 0.64 gm available lysine/MJ dietary energy (Edwards et al., 2013). As pig diets are further researched and refined to achieve the optimum lysine requirements, it is expected that all Australian pig diets will change to reflect these refinements. Table SI 3 shows the modifiers that were applied to the base diet for SAA based on manufacturing and application trends.

Table SI 3 SAA diet modifiers

Year	SAA
1980	0.2
1990	0.25
2000	0.5
2010	1
2020	1.25

7.2.1.5 Feed wastage

Feed wastage was estimated from the type of feed, feed presentation (feeder type) and predicted FCR. The type of feed used has been found to influence feed wastage. According to Roese (1990) the use of pellets in floor feeding can improve growth rate by 6-7% and FCR by 7-8% when compared to regular mash. The use of pellets in non-floor feeding system can also improve growth rate by 3.5% and FCR by 1.5% when compared to regular mash (Roese, 1990). Roese (1990) also concluded that the improvements in growth rates and FCR are most likely due to the lowering of feed wastage. Liquid feeding was found to improve FCR by 10% when compared to mash (Roese, 1990). Taylor and Clark (1990) found that conventional self-feeders commonly result in feed wastage of 6-15%, however, this can be reduced to 0.5% with wet/dry feeders.

According to Willis (1999) the typical feed waste percent of floor feeding mash was 27%, while the average feed wastage of non-floor feeding mash was 17% (ranging from 12-20%) and pellets were 7.6% (ranging from 5-10%) respectively.

Table SI 4 shows the feed presentation assumptions for the national Australian pig herd from 1980-2020. The proportion of floor feeding and non-floor feeding, together with reported FCR rates, were used to predict feed wastage levels.

Table SI 4 Feed presentation proportions for the national Australian pig herd from 1980-2020

Feed presentation	Floor fed	Non-floor fed	Reference
Unit	%	%	
1980	78	22	Ballantyne and Wrathall (1984).
1990	54	46	*Australian Pig Journal and survey*
2000	33	67	*Australian Pig Journal and survey*
2010	1	99	*Australian Pig Journal and survey*
2020	1	99	*Predicted by authors from trends.*

7.3 Housing and manure management systems

7.3.1 Housing definitions

Conventional housing refers to housing with partially or fully slatted floors where manure, urine, waste feed and water drop into channels or pits that are flushed or released regularly (generally twice per week) into open, anaerobic ponds. Outdoor housing refers to a system where pigs are allowed to range in an open paddock and are supplied with shelters. Deep litter refers to pigs being housed on litter (e.g. straw, sawdust, rice hulls) for the weaner, grower or finisher stage of production.

7.3.2 Emissions factors

Manure emissions were determined using the emission factors outlined in the Australian NIR (Commonwealth of Australia 2015), with the key factors shown in Table SI 5. These factors are not expected to change over time.

Table SI 5 Piggery livestock greenhouse gas parameters

Emission source	Emission and units	Factor
Maximum methane potential	Ultimate methane yield (Bo)	0.45
Manure – emissions from uncovered anaerobic pond		0.75 (NSW)
		0.77 (QLD)
		0.74 (VIC)
	MCF	0.77 (WA)
Manure – emissions from outdoor (dry lot)		0.01 (WA)
Manure – emissions from deep litter		0.04 (NSW)
		0.04 (WA)
Manure – emissions from uncovered anaerobic pond	N_2O-N [a]	0
Manure – emissions from outdoor (dry lot)	N_2O-N [a]	0.02
Manure – emissions from deep litter	N_2O-N [a]	0.01
Manure – emissions from uncovered anaerobic pond	NH_3-N [a]	0.55
Manure – emissions from outdoor (dry lot)	NH_3-N [a]	0.3

Manure – emissions from deep litter	NH_3-N [a]	0.125
Manure – emissions from stockpile	MCF	0.02 (NSW)
	MCF	0.02 (WA)
	N_2O-N [b]	0.005
	NH_3-N [b]	0.2
Indirect N2O from volatilised NH3	N_2O-N [c]	0.002

[a] kilogram per kilogram of N excreted, [b] kilogram per kilogram of N flow to the stockpile, [c] kilogram per kilogram of N volatilised as NH_3-N.

7.4 Feed production data

Feed production impacts were evaluated for each decade by determining feed efficiency factors, yields and inputs from historic data sources. This involved looking at historical trends for fertiliser use, herbicide use, crop yield, tillage events, machinery fuel efficiency, irrigation rate and percentage of crop from irrigated land. National data were used for all trends except the percentage of crop from irrigated land and number of tillage events, which are described in subsequent sections. The crop production models used in the LCA model ranged from 2008-2012. As a result, it was assumed that 2010 inventory was the base year (i.e. 100%) and the values from the other decades were ratioed accordingly to provide factors to adjust the model. The exceptions to this were tillage events which were given as a per year basis and percentage of crop from irrigated land which was used as is. It is important to note that 2010 was at the end of a substantial drought period in Eastern Australia (BoM, 2015) which influenced the trends.

Historical data for the national quantities of nitrogen, phosphorous and potassium fertilisers purchased (Fertilizer Australia, 2017) was divided by the total national crop area of wheat, barley, oats, maize and sorghum (ABS, 2012) to determine change in application rates. Due to data limitations, 1983 values were used to represent 1980 and 2017 values used to represent 2020. In accordance with Wiedemann et al., 2016b, manure was included as an input to the modelled cereal crop systems used in the feed inventory, representing 0.6% of cereal crop fertiliser requirements nationally and was built into the fertiliser modifier value. Historical data for the national quantities of 2,4-D and glyphosate herbicide applied to wheat crops (Department of the Environment and Energy, 2006) were divided by the national wheat production in ha (ABS, 2012). Yearly herbicide use data was available from 1997-2006 and a linear forecast was used to estimate use for previous and future years. The glyphosate use in 1980 was modified to reflect its introduction as an agricultural herbicide in 1974. Figure SI 2 shows the historical trend in fertiliser and herbicide use relative to the 2010 base year. Both fertiliser and herbicide use were found to follow a similar trend.

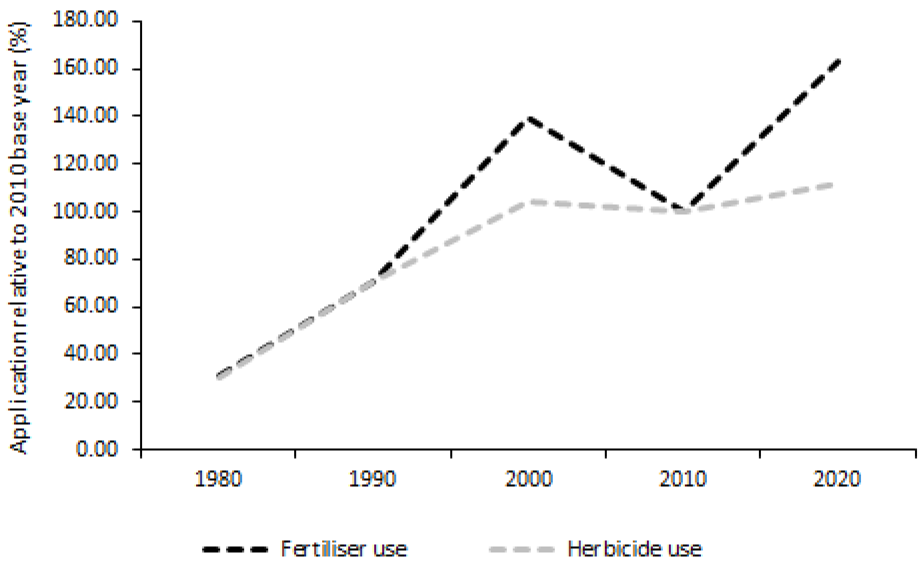


Figure SI 2 Historical Australian fertiliser and herbicide use relative to 2010 year base

Historical crop yield data in tonnes per hectare for wheat, barley and maize was taken from ABS for 1980-2010 (ABS, 2012) and used to forecast for 2020. The yield percentage relative to the 2010 base year was averaged for the three crops to remove any bias from higher yield crops. Figure SI 3 shows the historical trend of yield relative to the 2010 base year in 5-year increments from 1970-2020.

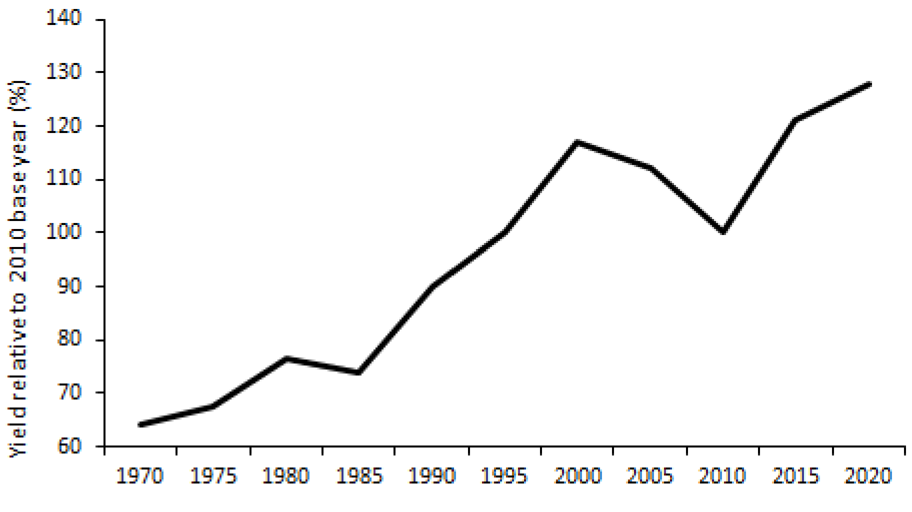


Figure SI 3 Historical Australian crop yield relative to 2010 base year

Historical data on the number of tillage or cultivation events in Australian crop production per hectare per year was extrapolated from Llewellyn et al. (2012) for 1980-2000 and from ABS (2011) for 2010 and from ABS (2018) for 2020. Figure SI 4 shows the average national number of tillage events per hectare per year.

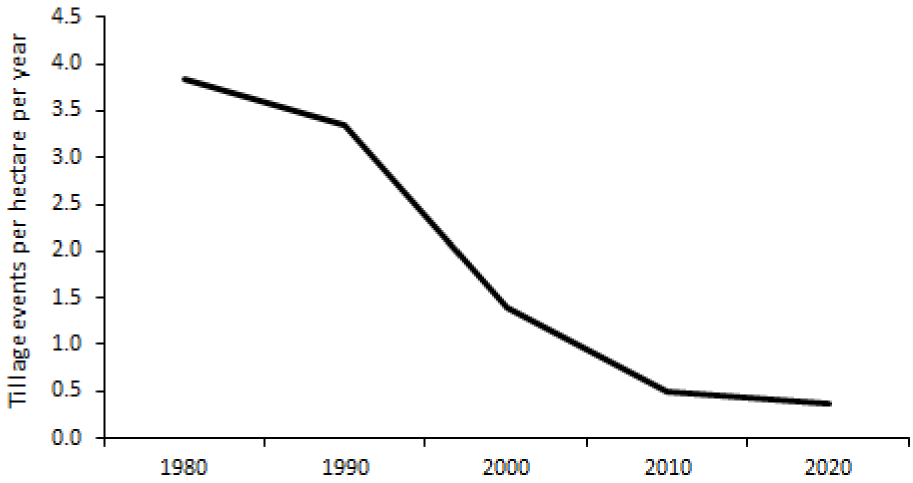


Figure SI 4 Historical Australian crop tillage events per hectare per year

Engine efficiency improvements in machinery used for grain production were determined by comparing the drawbar fuel efficiency of common tractors used for grain production in 1980 with tractors being used in 2018, using data from the Nebraska tractor tests reported by Tractor Data (Nebraska Tractor Test Laboratory, 2018). This was done by choosing a common mid-size tractor in 1980 (i.e. John Deere 6030, 111 kW drawbar power, 41.6 L hr-1) and a comparison tractor from the same manufacturer for 2018 (i.e. John Deere 8345R, 141 kW drawbar power, 58.7 L hr-1). These results showed drawbar fuel use (L kW-1) was 20% higher in 1980. Fuel use was consequently modelled using a linear interpolation of the rate of fuel efficiency improvement between 1980 and 2020 based on these data.

Historical irrigation data were taken from ABS (2005a, 2005b, 2006, 2008a, 2008b, 2009, 2010, 2011, 2013, 2014, 2015, 2016, 2017) and Watson et al. (1983) for the area of cereal grain irrigated, application rate per hectare and the total quantity of water applied to the land. Any missing values were calculated either from two of the other parameters when available or in the case of 1990 through total water applied to the land and a linear forecast of application rate using the remaining values. Data from 2015-17 was used to predict 2020 values. Where possible a two year average was used for the irrigation data to improve accuracy. The trend for irrigation application rate per hectare was calculated by using the 2010 value as a base value. The yield percentage from irrigated crop was calculated assuming that irrigated crops have a yield of 6 tonnes per hectare and that the non-irrigated crops were a weighted average of ABS yield data for wheat, barley, maize and oats. The yield rates were multiplied by the total irrigated and non-irrigated crop land area to give a ratio of total yield between the two. Extrapolated state values were calculated using the available state yield from irrigated land values from 2002-17 (ABS, 1999, 2001, 2005a, 2005b, 2006, 2008a, 2008b, 2009, 2010, 2011, 2012a, 2012b, 2013, 2014, 2015, 2016, 2017) and applying as an average against a national average of irrigated land area. Figure SI 5 shows the trend in contribution of irrigated grain to the total Australian crop.

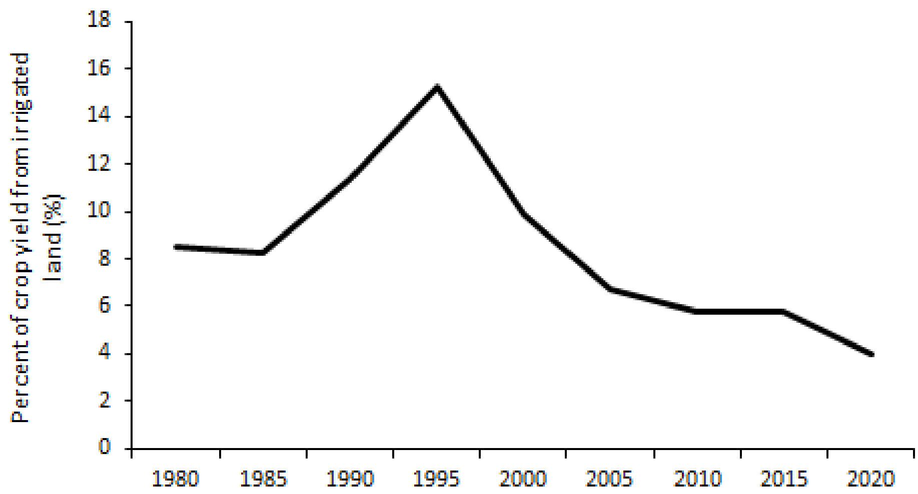


Figure SI 5 Percentage of Australian crop yield from irrigated crop land

7.5 General services, water and energy

7.5.1 Electricity generation data

Electricity generation throughout the period was investigated at both state and national level. Data was taken from the Department of Environment and Energy – Australian Energy update 2016 and 2017. The data covered the period 1973-2016; state data was available from 1995 onwards and national data was available throughout. A linear forecast was used to predict 2020 values. Due to the increased electricity load during the period, the most polluting energy mix was in the year 2000 as the extra demand was met at the time with coal. Table SI 6 shows the national mix of electricity production energy sources.

Table SI 6 Australian energy supply source for electricity production

Electricity energy source	1980	1990	2000	2010	2020
Black coal	51.11%	56.61%	58.96%	49.04%	35.83%
Brown coal	23.23%	21.71%	23.90%	22.22%	17.95%
Natural gas	9.28%	9.28%	7.74%	17.67%	23.98%
Oil	2.30%	2.30%	0.85%	1.23%	4.13%
Other[a]	0.00%	0.00%	0.00%	1.19%	0.00%
Biomass/Biogas	0.00%	0.48%	0.54%	1.10%	1.73%
Wind	0.00%	0.00%	0.03%	2.00%	7.00%
Hydro-electric	14.07%	9.62%	7.96%	5.37%	5.22%
Solar	0.00%	0.00%	0.02%	0.17%	4.17%

[a] Includes multi-fuel fired power plants

7.5.2 Direct Piggery Water Use

7.5.2.1 Water Source

Piggery water use is influenced by herd numbers, housing type, water source and the proportion of irrigation water use in rations. The proportion of different water sources is reported in Table SI 7.

Table SI 7 Piggery water resources the Australian national herd

	1980	**1990**	**2000**	**2010**	**2020**
Dam (%)	25%	18%	12%	5%	5%
Bore (%)	25%	45%	65%	85%	85%
River/Creek (%)	14%	11%	8%	5%	5%
Reticulated (%)	30%	22%	13%	5%	5%
Other (%)	6%	4%	2%	0%	0%

Data sources= 1980: Ballantyne and Wrathall (1984), 1990: Predicted by authors from trends, 2000: Predicted by authors from trends, 2010: Wiedemann et al., (2016) and 2020: Predicted by authors from trends.

7.5.2.2 Cleaning water for conventional piggeries

The medium flush cleaning system default (13 L. pig-1. day-1- PigBal 4) was used to estimate the cleaning water used for conventional piggeries. Additionally, change in recycled effluent use was investigated for each decade, and decade flushing water use adjusted accordingly (expert judgement) (Table SI 8). The following equation was used to determine cleaning water requirements:

Cleaning water requirement (ML. yr-1) = (1- recycled percent (%))*(Total herd flushing water (L. day-1)) * 365/1000000.

Table SI 8 Percent of cleaning flushing water supplied from recycled effluent over 1980 to 2020

Year	**Percent of cleaning water from recycled effluent**
1980	5%
1990	25%
2000	50%
2010	60%
2020	80%

7.5.2.3 Drinking water

The following equation was used to estimate water intake for each class of pig, based on average pig feed intakes (citied in Wiedemann, 2012).

WI=FI x Wf x Tf

Where: WI = Water Intake (L. pig-1. day-1)
FI = Feed intake (kg 'as-fed'. pig-1. day-1)

Wf = Water Intake factor, (2.5 for growing pigs, 2.8 for gestating/lactating sows)
Tf = Temperature factor, (1.6 for lactating sows, 1.2 for all other pigs)
A summary of drinking water intake by pig class is present in Table SI 19.

Table SI 9 Summary of drinking water intake by pig class

Pig class	**Feed ingested (as fed)** (kg. pig^{-1}. day^{-1})	**Wf** [1]	**Tf** [1]	**Calculated water intake** (L. pig^{-1}. day^{-1})
Gilts	2.50	2.5	1.2	7.50
Boars	2.30	2.5	1.2	6.90
Gestating sows	2.30	2.8	1.2	7.73
Lactating sows	4.50	2.8	1.6	20.16
Suckers	0.02	2.5	1.2	0.05
Weaner	0.90	2.5	1.2	2.70
Porker	1.75	2.5	1.2	5.25
Grower	2.45	2.5	1.2	7.35
Finisher	2.93	2.5	1.2	8.79

Wiedemann et al. (2012) reported drinking water wastage rates of 15 - 42%, which was influenced by a number of factors including drinker design, environmental factors, and pig behaviour. Similarly, Brooks (1994) found that growing/finishing pigs may waste up to 60% of the water from a nipple drinker, while Phillips et al., (1990) found that water wastage for sows can range from 23-80% of water use, depending on flow rate. Type of drinkers (e.g. trough, nipple, push-lever bowl, straw drinkers), drinker management and flow rate of the drinking water distribution system have a significant impact on drinking water wastage (Gonyou, 1996, Muhlbauer et al., 2011). The average PigBal drinking water wastage rate of 25% was used for 2010, with modifiers applied based on drinker type application and management trends (Table SI 10).

Table SI 10 Drinking water wastage modifiers over 1980 to 2020

Year	**Drinking water wastage modifier**
1980	1.6
1990	1.4
2000	1.2
2010	1.0
2020	0.9

7.5.2.4 Cooling water

Cooling water was estimated using recommendations from Taylor et al., (1994) and PigBal 4 default hours of cooling (540 hr per year, which is equivalent to 6 hr per day, over 90 days). Taylor et al., (1994) suggests spray cooling water use rates of 300 mL pig-1 hour-1 for sows, boars, grower and finisher pigs and a rate of 65 mL pig-1 hour-1 for weaners in Australian conditions.

Cooling water use (L. yr-1) = (pig number * 300 mL. pig-1. hour-1 * 540 hr per year)/1000.

7.5.2.5 Total water used

Table SI 11 describes the model assumptions used to calculate the total water use from each piggery type.

Table SI 11 Water use by piggery type

Piggery types	Total water used by piggery types
Conventional	Drinking water + drinking waste water+ cooling water + cleaning water
Deep litter	Drinking water + drinking waste water+ cooling water,
Outdoor	Drinking water + drinking waste water

7.6 Soil carbon and land use change

Emissions associated with land use and land use change for cropland were calculated from national emissions values reported in the NIR. The national emissions (CO2-e) and area of land use associated (ha) were used to calculate a national (CO2-e/ha) emissions factor for cropland. The cropland emissions from the NIR were grouped in two categories, "Cropland remaining Cropland" and "Land Converted to Cropland". Data for "cropland remaining cropland" includes land use associated with rotational cropping/grazing practices, and accounts for carbon stock change associated with management practices including tillage and stubble management. Land Converted to Cropland remains in the conversion category for 50 years, and the ongoing emissions associated with the land use change are reported each year. These emissions include the carbon stock change and soil emissions associated with the conversion of land to cropland. The greenhouse gas emissions arising from land use change were applied to the area of cropland required to produce the feed for 1kg of pork LW.

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