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Trends in the environmental impacts of the Australian pork industry

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ABSTRACT

Context. Over the past four decades, major changes have occurred in Australia's pork industry, affecting productivity and environmental performance. **Aims.** This study determined long-term changes in greenhouse gas and key resource use efficiency indicators. **Methods.** Life cycle assessment was used to determine impacts at decadal intervals between 1980 and 2010, and are presented alongside results for 2020 and 2022. **Key results.** Over 42 years since 1980, greenhouse gas emissions, excluding land use and direct land use change (dLUC), fell by 74% from 11.7 to 3.0 kg CO_2-e/kg liveweight. Land use and dLUC emissions declined by 92%. Fossil energy use decreased from 35 to 13 MJ/kg liveweight between 1980 and 2022. Freshwater consumption and water stress fell from 506 L and 671 L H_2O-e in 1980 to 52 L and 43 L H_2O-e/kg liveweight in 2022, respectively. Land occupation decreased by 42% from 22 m^2/kg liveweight in 1980 to 13 m^2/kg liveweight in 2022. Over the analysis period, emissions per kilogram of liveweight fell by an average of 1.8% per year, land use and dLUC emissions by 2.2%, greenhouse gas including land use and dLUC emissions by 1.9%, fossil energy use by 1.5%, and freshwater consumption, stress, and land occupation by 2.1%, 2.2%, and 1%, respectively. Between 2010 and 2020, uptake of covered anaerobic ponds resulted in an annual rate of improvement in emissions (excl. land use and dLUC) of 2.9%, however, the rate of improvement fell to 1.4% between 2020 and 2022. **Conclusions.** Long-term improvements were principally driven by improved herd productivity and feed production systems, and changes in housing and manure management. Herd and system efficiencies led to better feed conversion ratio, resulting in lower feed requirements, reduced manure production and lower feed wastage, which reduced manure greenhouse gas emissions. Concurrently, reduced tillage, higher yields, and a decrease in the proportion of irrigation water used for grain production resulted in lower impacts of feed grains. **Implications.** Ongoing changes and improvements in production efficiency have resulted in large gains in environmental performance in the Australian pork industry but new strategies will also be needed to maintain these trends into the future.

Keywords: agricultural systems, carbon footprint, energy, greenhouse gases, greenhouse gas emissions, land use change, life cycle assessment, pigs, pork, water.

Introduction

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), before the global pig herd peaked at 992 million head in 2015 (Dalgeish and Whitelaw 2021). The outbreak of African Swine Fever (ASF) in 2018 then saw the herd fall to its lowest level (850 million head) since 1997 (Dalgeish and Whitelaw 2021), however, the OECD/FAO (2022) projects that global pork production will recover to rise by 17% by 2031 from the ASF-reduced 2019–2020 base level. This long-term increase in pork production, and projected increase, 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 the pork supply chain emitting approximately 0.7 gigatonnes CO_2-e 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 CO_2-e per annum), but significantly lower than beef and bovine dairy production combined (4.6 gigatonnes CO_2-e per annum) (Opio *et al.* 2013).

In Australia, pig production 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 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 2021*a*) despite breeding herd numbers remaining fairly constant (ABS 1999, 2001, 2011*a*, 2021*a*). 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 projections indicate that Australian pork production will continue to increase over the next 5 years (ABARES 2023), though forecast drier than average conditions (i.e. drought) may influence this trend.

Herd productivity, and particularly feed conversion, is a key driver of change in environmental impact. Wiedemann *et al.* (2016) showed that production efficiency, and specifically herd feed conversion (HFC), explained 88% of the variation in GHG emissions from conventional Australian piggeries using the same manure management system (MMS). The strong association with HFC can be explained because this factor influences both upstream impacts associated with feed production, and downstream impacts associated with manure emissions. HFC 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.* (2018) 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 slaughter weight reduced environmental impacts per kilogram of pork produced. Noya *et al.* (2017) 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 through targeted improvement measures in feed use and manure management practices. Furthermore, pig housing and manure management systems (MMS) substantially influence GHG emissions from pork production (Chadwick *et al.* 2011; Philippe and Nicks 2015; Wiedemann *et al.* 2016), 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; Wiedemann *et al.* 2024), sheep (Benoit and Dakpo 2012), dairy (Capper *et al.* 2009) and pork production (Vergé *et al.* 2009; Boyd *et al.* 2012; Bonesmo and Enger 2021; Dai *et al.* 2021; Dorca-Preda *et al.* 2021; Fan *et al.* 2023). Wiedemann *et al.* (2023) showed a 22% decrease in carbon footprint, and a 73% decrease in water consumption associated with Australian beef production, between the intervals 1981–1985 and 2016–2020. 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 2020 and 2022 (from Copley *et al.* (2024)). An initial report of the work has appeared (Watson *et al.* 2018), however, that report did not include 2022 and the 2020 results were based on a projection.

Materials and methods

The study investigated GHG emissions using the Intergovernmental Panel on Climate Change (IPCC) AR5 global warming potentials of 28 for methane (CH_4) and 265 for nitrous oxide (N_2O), as applied in the Australian National Inventory Report (Department of Industry Science and Resources 2022). GHG emissions arising from LU and dLUC were calculated and reported separately following the guidance of ISO 14067 (ISO 2018). Energy demand was assessed using the fossil fuel energy demand method (Dones *et al.* 2007), and freshwater consumption and stress-weighted water use (Pfister *et al.* 2009) were also assessed. Modelling was conducted using SimaPro 9.4 (Pré-Consultants).

System boundaries and declared unit

The study examined the primary production system (i.e. cradle to farm-gate) using a declared unit of 1 kg of live weight (LW), 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 transport to meat processing. The herd was modelled at 10-year intervals, and at a 2-year interval in the most recent time step.

Inventory data

Australian national herd data

For 1980–2010, a model of the Australian pig herd was developed for each time period using national herd statistics (see Table 1) and industry herd performance data (Table 2). Herd numbers were accessed from the annual survey of Australian farms (ABS 1999, 2001, 2011*a*), which included breeder and grower pig numbers and was supported by primary data surveys (see Wiedemann *et al.* 2016). Data were averaged for 2-year intervals at the end of each decade, to smooth market fluctuations. An independent dataset of the total number of pigs slaughtered, and total carcase weight (ABS 2021*b*) was available to determine the total output of the herd. For 2020 and 2022, the national herd and industry herd performance were determined in Copley *et al.* (2024) from industry surveys and national statistics and were reported for one financial year only (i.e. not averaged) as the analysis is now being conducted more frequently.

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 for 1980 to 2010, but for 2020 and 2022 industry survey data were used (Copley *et al.* 2024). 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, 1999, 2000; Cleary and Godfrey 2002; Cleary *et al.* 2003; McElhone and Philip 2004, 2005; Dowling 2006; Walsh and Bottari 2008; APL 2011, 2012; Wiedemann *et al.* 2016, 2018), a livestock balance was developed for the herd that accounted for breeder mortality, breeder replacement rates and HFC of pigs from birth to slaughter. The average age of finisher pigs was determined by dividing average sale weight minus birth weight, by ADG. Pigs sold per sow per year (Table 2) was assumed to be the total number of pigs slaughtered divided by the total number of sows (both reported in Table 1).

For 1980–2010, feed intake and diets were determined for each decade for each major production region in Australia, via consultation with industry nutritionists and from primary data. 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

Table 1. National pig herd data based on Australian primary data.

Category	Units	1980	1990	2000	2010	2020[A]	2022[A]
Total sow numbers	Pig/year	272,273	301,539	264,337	236,936	246,037	261,417
Total boar numbers	Pig/year	21,066	21,745	15,977	9240	1231	1308
Total slaughter pigs	Pig/year	3,784,400	4,944,600	5,025,950	4,558,400	516,700	5,629,488
Total slaughter weight produced (dressed weight, DW)	Tonne	211,636	314,741	363,282	331,203	402,706	449,691

[A]See Copley *et al.* (2024).

Table 2. National Australian pig herd performance data.

Category	Units	1980	1990	2000	2010	2020[A]	2022[A]
Weaning age[B]	days	34.3	24.5	21.0	23.2	22.3	22.3
Litters per sow per year[B]	#	2.1	2.2	2.2	2.3	2.3	2.3
Pigs born alive per sow per year[B]	#	19.6	22.9	22.6	24.8	22.8	22.8
Pigs weaned per sow per year[B]	#	14.7	19.9	19.4	21.5	21.7	21.7
Pigs sold per sow per year[B]	#	13.9	16.4	19.0	19.2	20.5	20.9
Liveweight sold per sow per year[C]	kg	1022.4	1373.7	1807.9	1839.5	2103.8	2176.1
Average sale weight of finisher pigs[D]	kg	75.0	84.9	96.0	95.6	100.0	102.0
Average age of finisher pigs[D]	days	187.6	169.0	164.0	150.5	151.0	150.3
Average daily gain (wean–finisher slaughter)[E]	gram/day	500.4	568.0	586.0	636.0	655.0	669.7
Progeny FCR[E]	kg feed/kg LW	3.5	3.1	2.9	2.5	2.4	2.3
HFC[B]	kg feed/kg DW	7.1	5.9	4.8	4.2	3.8	3.8

DW, dressed weight.
[A]Derived from Copley *et al.* (2024).
[B]Literature value derived from multiple sources, see Supplementary material.
[C]ABS (1999, 2001, 2011*a*, 2021*a*).
[D]ABS (ABS 2021*a*), dressing percentage was altered by 0.5% between decades from 74.5% in 1980 to 76% in 2010.
[E]1980–2010: modelled using PigBal (Skerman *et al.* 2015).

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. Using these data, the herd was modelled each decade using Pigbal 4 (Skerman *et al.* 2015) to determine feed use, FCR and ADG.

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 carbon footprint and resource use. In Australia, pig housing can be categorised into three broad types: outdoor, conventional and deep litter (Wiedemann *et al.* 2016). As shown in Table 4, outdoor housing has one MMS. Deep litter housing has a limited number of MMS (related to spent litter handling), whereas 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 1990–2010 were reported in the Australian National Inventory Report (NIR) (Commonwealth of Australia 2021) and were applied in the study. Housing type and MMS for 1980 were determined from Ballantyne and Wrathall (1984) and personal communications with industry researchers (K Casey, pers. comm.). Housing and MMS for 2020 were determined using data from the NIR (Commonwealth of Australia 2021) and Copley *et al.* (2024).

Manure production and management emissions

Manure production was modelled using methods for predicted manure excretion and feed waste from 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. For 1980–2010, feed waste was a predicted input to the manure stream. Manure emissions were determined using the emission factors outlined in the NIR (Commonwealth of Australia 2021) and were inclusive of system losses. In accordance with

Table 3. Ration components and diet properties for pig feed over the time period 1980 to 2022.

Ration component	Unit	1980	1990	2000	2010	2020[A]	2022[A]
Barley	%	10.84	17.55	19.96	22.13	29.47	24.98
Sorghum	%	16.19	12.34	10.72	14.31	1.48	3.11
Wheat	%	48.38	47.19	49.75	45.14	37.29	39.82
Lupins	%	1.79	2.05	2.64	1.54	1.09	2.36
Field peas	%	2.75	3.70	3.91	3.34	2.71	5.87
Bloodmeal	%	2.07	0.93	1.12	1.10	0.00	0.00
Meat and bone meal	%	11.55	8.93	3.62	2.83	3.60	3.77
Canola meal	%	0.00	0.60	1.00	3.20	9.93	7.04
Soymeal	%	0.50	2.08	3.80	3.40	2.70	2.60
Other protein meal/tallow	%	3.57	2.37	1.20	0.50	1.39	1.00
Vegetable oil	%	0.86	0.82	0.48	0.37	0.45	0.52
Diverted food waste, residuals, by-products	%	–	–	–	–	6.49	5.90
Low-cost additives	%	1.34	1.19	1.44	1.44	1.80	2.05
High-cost additives	%	0.16	0.25	0.36	0.70	1.61	1.36
Feed dry matter	%	89.02	88.80	88.47	88.48	89.08	89.20
Diet ash	%	6.71	5.78	4.40	4.18	4.90	4.90
Crude protein	%	19.64	18.36	17.24	16.82	17.49	17.41
Dry matter digestibility (DMD)	%	76.94	79.46	81.72	83.31	82.36	81.90
Feed wastage	%	19.40	15.70	11.40	7.90	5.90	5.80

Notes: diets represent a weighted average of breeder, weaner and grower finisher diets, averaged across all major production regions.
[A]Based on data from Copley *et al.* (2024).

Table 4. Proportion of manure treated in different manure management systems in the Australian herd from 1980 to 2022.

Housing system	MMS	Units	1980[A] (%)	1990 (%)	2000 (%)	2010 (%)	2020[B] (%)	2022[B] (%)
Outdoor	Spread to pasture	%	5.0	3.0	5.0	5.1	7.8	8.2
Deep litter[C]	Solid storage	%	0.0	1.0	24.8	21.7	31.1	30.9
Conventional	Effluent pond[D] (uncovered anaerobic pond)	%	84.4	90.0	66.4	63.8	34.8	35.9
	Anaerobic digester/covered pond	%	0.0	0.4	0.3	6.2	19.0	17.7
	Short HRT tank storage (<1 month)	%	9.4	2.0	1.4	1.4	1.4	1.4
	Solid separation and solid storage	%	1.2	3.6	2.1	1.8	5.9	5.9

[A]Authors estimation from personal communication with industry experts.
[B]From Copley *et al.* (2024).
[C]5% of volatile solids is assumed to be lost in the primary system (Wiedemann *et al.* 2014).
[D]Secondary MMS from covered pond/digester is an uncovered pond, and 75% of volatile solids is assumed to be lost in the primary system (Wiedemann *et al.* 2014).

Wiedemann *et al.* (2016) 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%.

Feed grain system inputs

Feed grain inputs were modelled using inventory data from Wiedemann *et al.* (2016) and the Australian National Life Cycle Inventory Database (AusLCI) (ALCAS 2017). Feed grain processes were developed for the time periods from 1980 to 2000 to reflect crop yield, crop irrigation and tillage practices from national statistics (Watson *et al.* 1983; ABS 1999, 2001, 2005, 2011*a*; 2011*b*, 2020, 2021*a*, 2021*c*; Llewellyn *et al.* 2012). Fuel use was adjusted in response to changes in tillage and to reflect changes in engine efficiency for agricultural equipment over the analysis period. Fertiliser and herbicide usage over the time period was determined from national purchase data (Dept. Env and Energy 2006). Additionally, the total land occupation for crop production was determined from reported crop yields each decade (ABS 1999, 2001, 2011*a*, 2012, 2021*a*).

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 1999, 2000; Cleary and Godfrey 2002; Cleary *et al.* 2003) and Wiedemann *et al.* (2016). These datasets showed energy use was 19.7% higher for the 3 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 for 1980–2010 in both deep litter and outdoor production systems were based on Wiedemann *et al.* (2016), modified to reflect improved efficiency using the same method as in feed production.

Table 5. Aggregated general services and energy inputs for national pig production (on-farm) for each decade from 1980 to 2022.

Input	Parameter	Units	1980	1990	2000	2010	2020[A]	2022[A]
Materials	Purchased feed (as fed)	kg/100 kg LW	519.00	440.10	361.90	318.90	289.10	286.78
Services, conventional	Diesel	L/100 kg LW	0.59	0.55	0.53	0.51	0.48	0.50
	Petrol	L/100 kg LW	0.25	0.24	0.23	0.22	0.10	0.14
	LPG	L/100 kg LW	0.45	0.39	0.34	0.28	0.60	0.50
	Electricity	kWh/100 kg LW	35.34	30.96	26.59	22.21	20.95	22.5
	Piggery water use	L/kg LW	93.65	48.63	28.34	23.08	25.61	25.17
Services, deep litter/outdoor	Diesel	L/100 kg LW	1.27	1.20	1.14	1.10	1.08	1.29
	Petrol	L/100 kg LW	0.18	0.17	0.17	0.16	0.22	0.28
	LPG	L/100 kg LW	0.56	0.49	0.42	0.35	0.01	0.00
	Electricity	kWh/100 kg LW	4.69	4.11	3.53	2.95	0.87	1.07
	Piggery water use	L/kg LW	22.43	20.92	14.79	12.88	17.32	11.94

LPG, liquefied petroleum gas.
[A]From Copley *et al.* (2024).

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 for 1980–2010 (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 (Li et al. 2005; Apostolidis et al. 2011; Muhlbauer et al. 2011; Holyoake et al. 2018).

Land use and direct land use change emissions

Land use and direct land use change (LU and dLUC) emissions and removals from Australia cropland were determined from the National Greenhouse Accounts (Commonwealth of Australia 2023) over the period 2000–2022. Methods are described in detail in Copley et al. (2024) and are not repeated here. Emissions from cropland prior to 2000 were determined using a linear hindcasting method.

Imported soybean meal (another source of LU and dLUC emissions) was modelled to reflect the Australian import market in each decade (OEC 2020; Index Mundi 2023).

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 (see Wiedemann et al. 2016). 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 'liveweight' 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. (2016). Manure was included as an input to the modelled cereal crop systems used in the feed inventory.

Scenario analysis

Scenario analysis was conducted to determine how changes in the proportion of effluent treated in different manure management systems and changes in herd feed conversion would affect the carbon footprint of Australian pork production. The objective of the analysis was to understand what degree of change in the carbon footprint of pig production could be expected by 2032 (i.e. projected forward 10 years) if these production changes were realised.

Scenario 1 assumed that 70% of effluent from conventional production was treated in covered anaerobic ponds. Compared with the FY22 values in Table 4, conventional effluent ponds (uncovered anaerobic ponds) accounted for 11% of manure treated in the Australian herd, and anaerobic digesters/covered ponds accounted for 42.6% by 2032. All other parameters (including the proportion of manure treated in outdoor, deep litter and other conventional systems) remained unchanged from the 2022 inventory.

Scenario 2 was based on a change in herd feed conversion of 8% to 3.5 by 2032. As a simplification for the purpose of the analysis, all other parameters remained unchanged from the 2022 inventory.

Scenario 3 assumed both the changes from Scenario 1 and Scenario 2 were combined as these were complementary.

Results

Trends in Australian pig production

Herd productivity

There have been considerable productivity improvements in the Australian pork industry over the last 42 years. Although sow numbers remained relatively stable over the analysis period, pigs slaughtered and total sale weight have increased substantially (see Fig. 1a, b), indicating that herd productivity improvements rather than herd expansion was the main driver for increased production. These productivity improvements include increased number of pigs born alive, pigs weaned, and pigs slaughtered per sow (Fig. 1c), increased average sale weight of pigs sold (Fig. 1d), increased average daily gain in growing pigs and improved herd feed conversion (HFC) (Fig. 1e).

Housing and manure management systems

Conventional housing represented approximately 95% of all pig housing in the 1980s and 1990s, however this fell to approximately 60% following the introduction of deep litter housing in the late 1990s. In 2022, nearly one-third of pigs were produced in deep litter systems (Fig. 2). Although there was a small decrease in the 1990s, outdoor production has increased slightly over the analysis period, accounting for 8% of the industry housing in 2022. The conventional housing MMS changed considerably over the 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 reached a local maximum in the 1990s but declined after this until peaking at 5.9% in 2022. The use of uncovered anaerobic

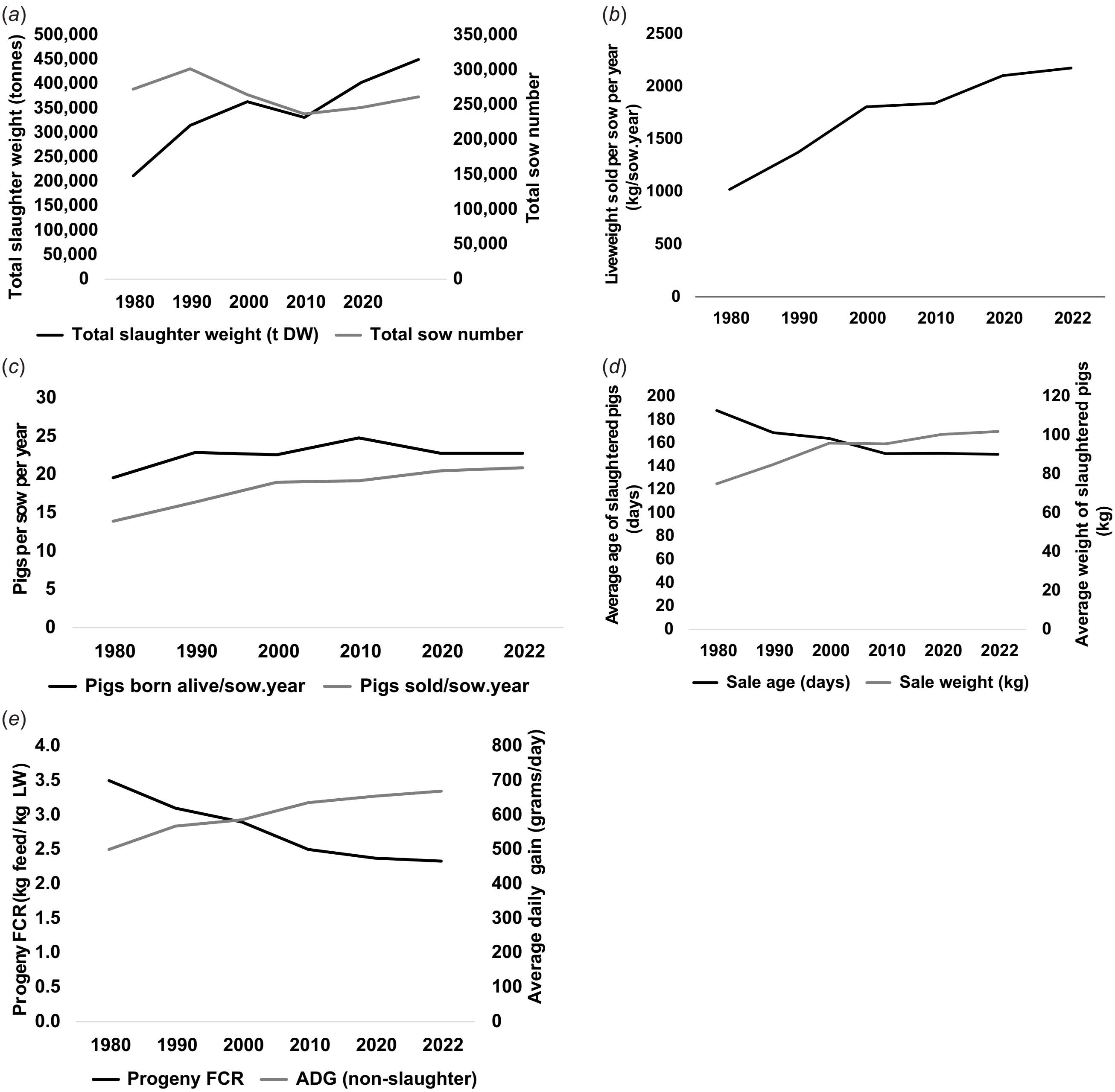

Fig. 1. Herd productivity improvements in the Australian pig herd over the period 1980–2022. (*a*) Total sow numbers compared to total slaughter weight (Dressed Weight, DW) produced from the Australian herd, (*b*) Liveweight sold per sow per year, (*c*) Pigs born alive per sow per year compared to pigs sold per sow per year, (*d*) Comparison of average sale age (days) to average sale weight (kg), and (*e*) Comparison of progeny FCR to average daily gain (wean to slaughter).

ponds peaked in the 1990s and steadily decreased since, in response to the introduction of deep litter in the 2000s and more recently the introduction of anaerobic digesters and covered ponds.

Trends in environmental impacts and resource use

Environmental impacts of Australian pork production from 1980 to 2022 are reported per kilogram of LW in Supplementary Table S1.

GHG emissions

The analysis revealed a 74% decline in GHG emissions (excl. LU and dLUC), from 11.7 kg CO_2-e/kg LW in 1980, to 3.0 kg CO_2-e/kg LW in 2022 (Table S1). Emissions from the MMS were the largest emission source, ranging from 70% of total impacts in 1980 and 1990, to 49% in 2022 (Fig. 3). Emissions from the MMS declined in absolute and proportional terms over the analysis period, reflecting the change to lower carbon footprint systems such as deep litter (DL) and anaerobic

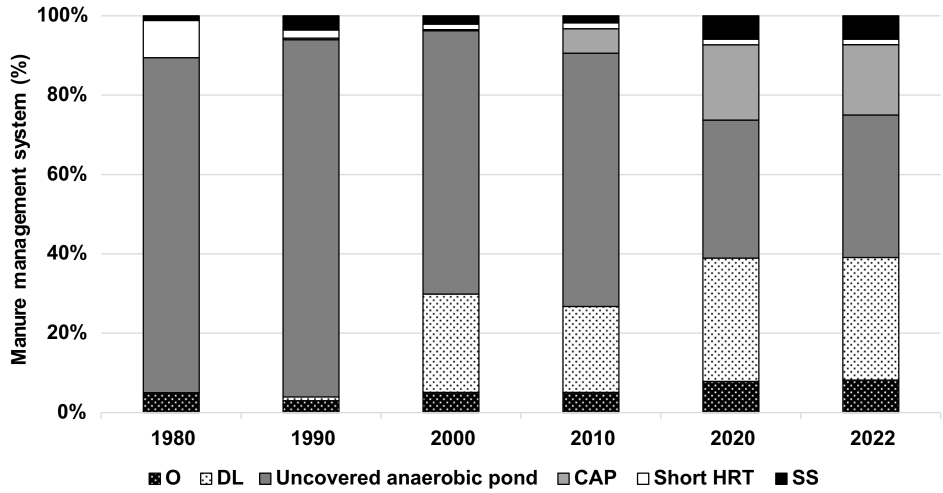

Fig. 2. Changes in manure management systems over the period 1980–2020 for the Australian pig herd. Notes: O, outdoor, manure directly deposited to land; DL, deep litter; uncovered anaerobic pond, conventional housing with uncovered anaerobic pond MMS; CAP, conventional housing with anaerobic digester/covered pond MMS; Short HRT, conventional housing with short hydraulic retention time MMS; SS, conventional housing with solid separation MMS).

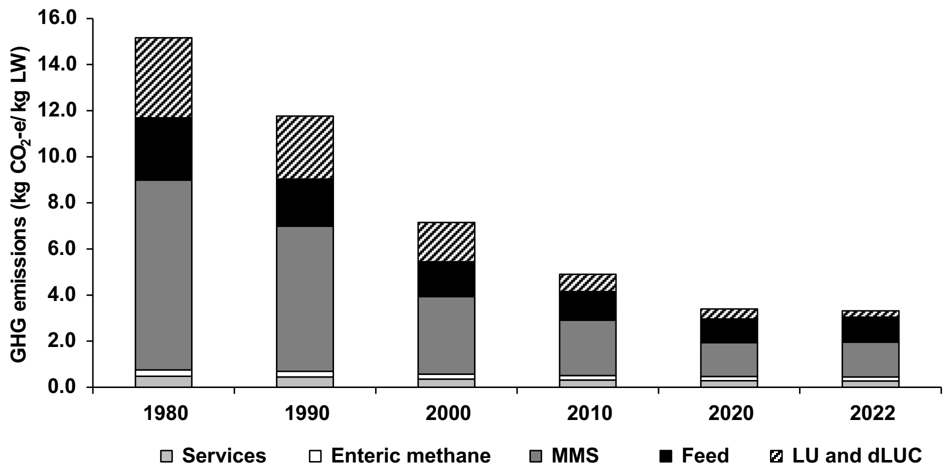

Fig. 3. Changes in greenhouse gases emissions (including LU and dLUC) from the production of 1 kg of live weight pork over the period 1980–2022.

digesters or covered ponds and in response to reduced flows of manure and feed waste to the MMS per kg of LW. Feed production contributed 23% of GHG emissions in both 1980 and 1990, which increased to 36% in 2022, indicating improvements in piggery systems were greater than improvements in grain production. 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 92%, from 3.5 kg CO_2-e/kg LW in 1980 to 0.3 kg CO_2-e/kg LW in 2022, principally because of the change from tillage to zero tillage in grain production systems, and changes in production systems and volumes of imported soymeal.

Total emissions for the industry from 1980 to 2022 were calculated and are reported in Table S2 by greenhouse gas. Over the analysis period, total emissions (including LU and dLUC emissions) fell by 56%. The bulk of the reduction was attributable to reduced soil carbon loss from Australian cropland as LU and dLUC emissions fell by 82% over the analysis period whereas GHG emissions (excluding LU and dLUC emissions) fell by 47%. Since 2000, the average rate of reduction in total emissions has also slowed, from 30% between 1990 and 2000 to 38% between 2000 and 2010 (driven by uptake of covered anaerobic ponds) before more than nearly halving to 16% between 2010 and 2020, i.e. from 3 to 4% per year to less than 2%, before increasing by 7% between 2020 and 2022.

Fossil energy use

Fossil fuel energy declined 61% over the analysis period, from 34.6 MJ/kg LW in 1980, to 13.4 MJ/kg LW in 2022 (see Table S1). Fossil fuel energy was primarily associated with feed grain production, and substantial declines in absolute fossil fuel energy were observed over the analysis period (Fig. 4). The contribution of feed to total energy also declined from 83% of fossil fuel energy in 1980 to 73% in 2022. The contribution of services (i.e. energy used at the piggery) also decreased in absolute terms over the analysis period, but increased slightly in proportional terms, from 17% in 1980 to 27% in 2022, indicating that energy efficiency improvements were less pronounced in piggeries than in grain production systems although the increased prevalence of ventilated systems (as opposed to naturally ventilated in the past), i.e. a new source of energy demand, may be a contributing factor.

Fresh water consumption and stress-weighted water use

Fresh water consumption was 505.9 L/kg LW in 1980, declining to 52.5 L/kg LW in 2022, representing an 90% reduction in water consumption over the analysis period (see Table S1). Stress-weighted water use followed a similar trend, decreasing by 90%, from 671.4 L H_2O-e/kg LW in 1980 to 24.3 L H_2O-e/kg LW in 2022. Irrigation associated with feed production was the single largest source of freshwater consumption, contributing over 82% in 1980, peaking at 91% in 2000, then falling to 56% in 2022 (see Fig. 5). Although the proportionate contribution of piggery water consumption increased from 18% in 1980 to 44% in 2022, the absolute contribution fell by 69% over the analysis period.

Land occupation

Land occupation declined 42%, from 21.9 m^2/kg LW in 1980 to 12.7 m^2/kg LW in 2022 (see Fig. 6) in response to reductions in feed requirements (i.e. improved FCR) and

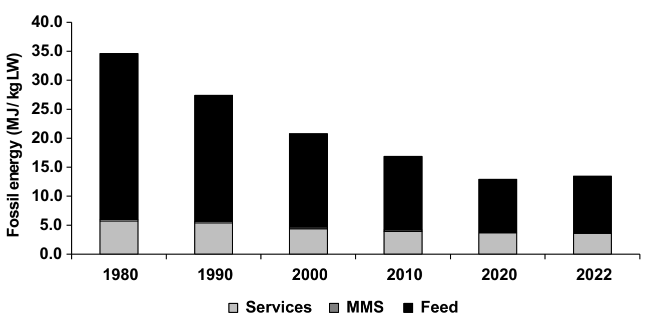

Fig. 4. Changes in fossil energy use from the production of 1 kg of live weight pork over the period 1980–2022.

increased grain yields in the feed grain production system. Interestingly, although land occupation impacts fell by an average of 10% each decade, between 2000 and 2010, impacts fell by only 3% (see Table S1) because of the lower yields reported in these drought years (Bureau of Meteorology 2015).

Scenario analysis

Results of the scenario analysis are outlined in Fig. 7 per kilogram of LW. Scenario 1 yielded an 18% reduction in the carbon footprint, driven by a 41% reduction in emissions from MMS. Scenario 2 resulted in an 8% reduction, and Scenario 3 a 24% reduction, noting the impact of both scenarios was slightly less than may be expected, because the impact of improvements in HFC on MMS emissions diminished with lower emission MMS.

Discussion

Environmental impacts and resource use associated with Australian pork production have 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 have led to a decrease in both upstream impacts associated with grain production, and emissions associated with manure management. These influences are described in the following sections.

The influence of changes in herd productivity

During the analysis period, pork production per breeding sow (LW sold/sow.year) increased 113%, in response to a 32% increase in pigs sold per sow and a 50% increase in the average liveweight of pigs at slaughter. In addition, average daily gain increased 34%, resulting in (20%) faster turnoff. These changes contributed to substantial improvements in HFC (47% over the analysis period). 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 pigs per litter, FCR, 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). Bonesmo and Enger (2021), Wang *et al.* (2017), MacLeod *et al.* (2013), Garnett (2011), Kingston *et al.* (2009) and Piot-Lepetit and Moing (2007), found that increases in pig productivity

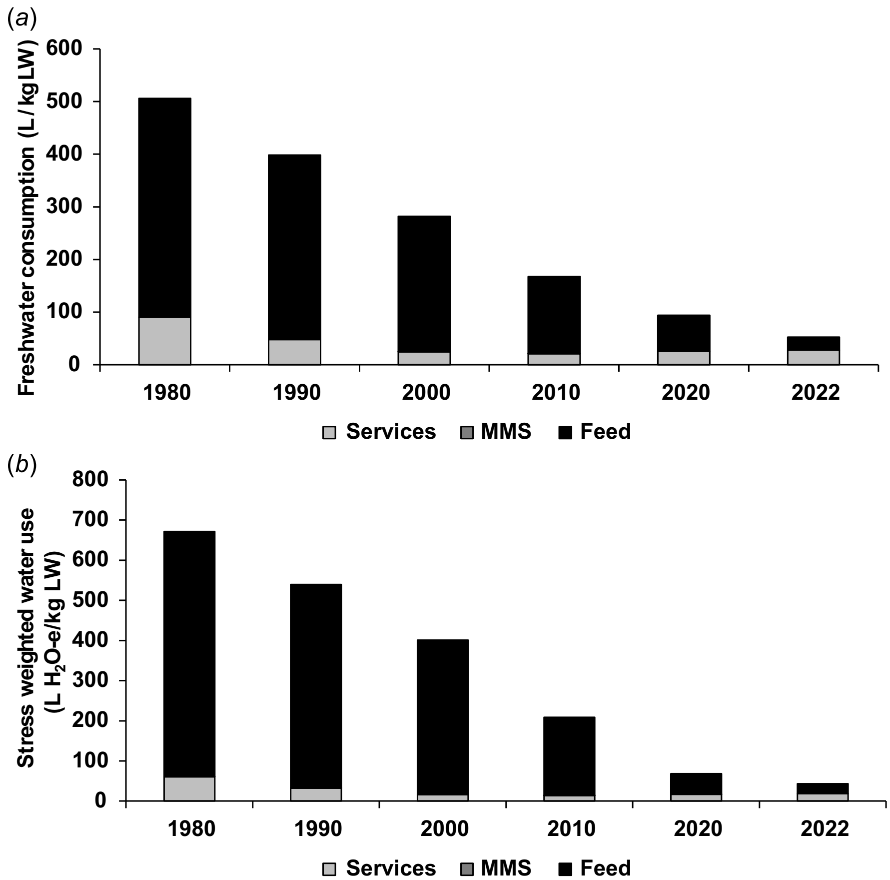

Fig. 5. Changes in water consumption (*a*) and water stress (*b*) from the production of 1 kg live weight pork over the period 1980–2022.

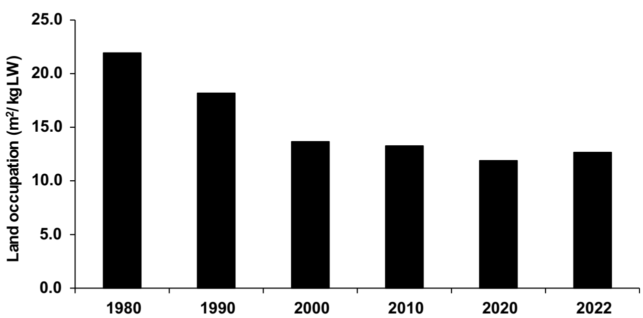

Fig. 6. Changes in land use from the production of 1 kg live weight pork over the period 1980–2020.

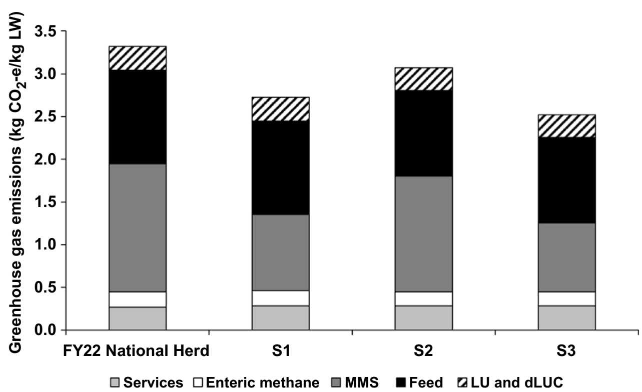

Fig. 7. Changes in greenhouse gas emissions (including LU and dLUC) per kilogram of liveweight under emission reduction scenarios.

resulted in a significant decline in GHG emissions. Furthermore, several international studies on different animal production systems have shown that increasing animal productivity significantly reduces carbon footprint (Wall *et al.* 2010; Garnett 2011; Gerber *et al.* 2011; Ripoll-Bosch *et al.* 2013; Hyland *et al.* 2016; 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 (Vergé *et al.* 2009), and for Australian beef cattle by Wiedemann *et al.* (2023). Dorca-Preda *et al.* (2021) also reported higher liveweight gain (and better FCRs) over time contributing to lower GHG emissions in Danish pig production.

In parallel to genetic improvements, pig nutrition has advanced to deliver better growth rates and improved feed conversion. These improvements include phase feeding, nutrient optimisation, digestibility improvements, use of enzymes and synthetic amino acids (SAA) (Radcliffe *et al.* 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 to avoid over-consumption of protein and to maximise lean growth. This is especially important to maximise lean growth potential in modern, genetically improved, high-lean genotype pigs (Coffey *et al.* 2017). Combined with increased use of SAA, the overall dietary crude protein (CP) was observed to decrease by 11% between 1980 and 2020, which in turn resulted in lower nitrogen excretion and therefore lower manure-related nitrous oxide emissions. The relationship between reduced dietary CP and reduced GHG has been shown by a number of studies (Canh *et al.* 1998; Zervas and Zijlstra 2002; Le *et al.* 2008; Kaufmann 2015; Sajeev *et al.* 2018; Seradj *et al.* 2018; Trabue *et al.* 2021).

The increased use of SAA in pig diets has also made possible diet formulations with lower proportions of meat proteins and higher levels of cereal grains. Over the analysis period, animal proteins declined from 17.2% of the diet in 1980 to 4.8% in 2022, 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 (Simmons *et al.* 2019) whereas protein meals are more emission intensive, particularly in the case of imported soymeal (Arrieta *et al.* 2018) and animal protein meals. Thus, these changes in the proportion of different commodities have contributed to lower impact diet formulations.

In the present study, diet digestibility was found to increase by 6.5% between 1980 and 2022, due to changes in the composition of diets, and the use of enzymes. Changes in feed processing, including the optimisation of diet particle sizes and use of pelleted diets, also improved digestibility and feed efficiency (Owsley *et al.* 1981; Goodband *et al.* 1995; Wondra *et al.* 1995; Bao *et al.* 2016; Fan *et al.* 2017). Improved digestibility is a likely contributor to the higher reported growth rates and improved feed efficiency in the herd over the analysis period, and led to lower predicted manure excretion rates and subsequent GHG emissions from the MMS.

In addition to improvements in feed formulation, better feeding systems resulted in a decline in feed wastage. Feed wastage in piggeries can be a substantial loss and is difficult to measure directly. Consequently, HFC 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 70%, 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 and feeder design (floor fed to non-floor feeding), and feed processing (optimising feed particle size for pig stages) (Roese 1990; Taylor and Clark 1990; Willis 1999; Mullan *et al.* 2011; Patience *et al.* 2015). This contributed to better FCRs, and also reduced the volatile solids (VS) lost to the MMS directly from wasted feed. As VS from feed waste have been shown to contribute substantially to MMS GHG emissions (Manyi-Loh *et al.* 2013; Wiedemann *et al.* 2016), this trend was a contributing factor to lower GHG emissions from MMS over then analysis period.

These improvements in herd productivity, feed formulation and feed waste resulted in an estimated 32% improvement in progeny FCR and 46% improvement in HFC over the analysis period. In their analysis of case study piggeries, Wiedemann *et al.* (2016) 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 environmental impacts from pork production over time.

The influence of housing and MMS changes

Differences in housing and MMS can have a significant effect on GHG emissions from pork production (Amon *et al.* 2006; Rigolot *et al.* 2010; Cherubini *et al.* 2015; Philippe and Nicks 2015; Wiedemann *et al.* 2016; Dennehy *et al.* 2017). 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.* (2016), 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 proportionate increase in DL housing (over conventional housing with uncovered anaerobic ponds) was one factor leading to lower GHG emissions and to a lesser extent, lower fossil energy use and freshwater consumption at the piggery.

During the 22 years to 2022, the proportion of manure treated in covered anaerobic ponds or digesters increased from less than 0.5–17.7% (see Table 4), leading to substantial further reductions in GHG emissions and energy demand per kilogram of LW. In comparative terms, Wiedemann *et al.* (2016, 2018) 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, relatively recent trend that has led to lower environmental impacts.

Several international studies, including Pexas *et al.* (2020), have shown that the adoption of biogas can significantly reduce the carbon footprint 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, and 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. Within systems with anaerobic digesters, Ramírez-Islas *et al.* (2020), demonstrated that producing renewable energy from biogas was environmentally optimal (as opposed to flaring).

Over the analysis period, energy demand for operating the piggery (piggery services) declined by 38%. 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 (Brumm *et al.* 2000; Brumm 2006, 2010; Alvarez-Rodriguez *et al.* 2013; Pype and Tait 2018).

The influence of feed production changes

Feed impacts arise from field operations, fertiliser emissions, transport and milling and are typically a major source of environmental impacts for pork production (Reckmann *et al.* 2013; Pirlo *et al.* 2016; Arrieta and González 2019; Pexas *et al.* 2020). 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 a 29% and 43% decrease in GHG emissions (excluding LU and dLUC) and fossil fuel energy demand per tonne of pig feed between 1980 and 2022. Over the same period, freshwater consumption and water stress was found to decrease by 86% and 92% per tonne of pig feed, while land occupation declined by 17%. This period corresponded to a substantial 46% yield increase for Australian broadacre crops and 90% and 16% reduction in tillage events and machinery fuel use respectively (see Fig. 8*a*), though fluctuations were observed in response to drought conditions around the year 2010 (ABS 2012).

The uptake of zero tillage was a notable change during the analysis 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 resulted in reduced fuel requirements and substantially reduced land use (soil) carbon losses. The moderation in soil carbon losses in Australian cropland considerably reduced LU and dLUC emissions (by 99%) per tonne of feed, which fell from 2.0 to 0.1 t CO_2-e between 1980 and 2022. 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 emissions and energy were less pronounced between 2010 and 2020, largely because the uptake of zero tillage slowed (see Fig. 8*b*) as it reached very high uptake levels, leaving little room for further improvement. Additionally, yield increases were accompanied by higher fertiliser and herbicide usage (Angus and Grace 2017; Watson *et al.* 2018), resulting in little improvement in GHG emissions or energy demand per tonne of feed over this period. In contrast to this, the increase in yield resulted in further declines in land occupation of 20% over this decade.

Changes in freshwater consumption over the analysis period were driven by different trends compared with GHG emissions, fossil energy use, and land occupation. Freshwater 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, fell by 53% between 1980 and 2022.

The application rate of water per hectare also reduced by 52% over the analysis 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 79%. This is illustrated in Fig. 8*c*, which shows the proportion of total crop yield from irrigated cereal grain over the analysis period. The contribution of irrigated crops was found to peak in the 1990s, then to fall steadily through to 2020 in response to ongoing reductions in irrigation water use for cereal grains.

Comparison with literature

Intensive animal production systems are complex, and comparing between jurisdictions and contemporary vs historical data is made more challenging by inter-changing similarities and differences. Australian pork production, for example, is the beneficiary of lower carbon footprint production of feed grains but also has generally higher carbon footprint grid electricity supply and experiences higher methane conversion factors in MMS than cooler climates. Across the available trends studies, as in this one, pork production systems have all undergone changes in manure management systems and benefited from increased production efficiency over time, leading to generally lower impacts over time.

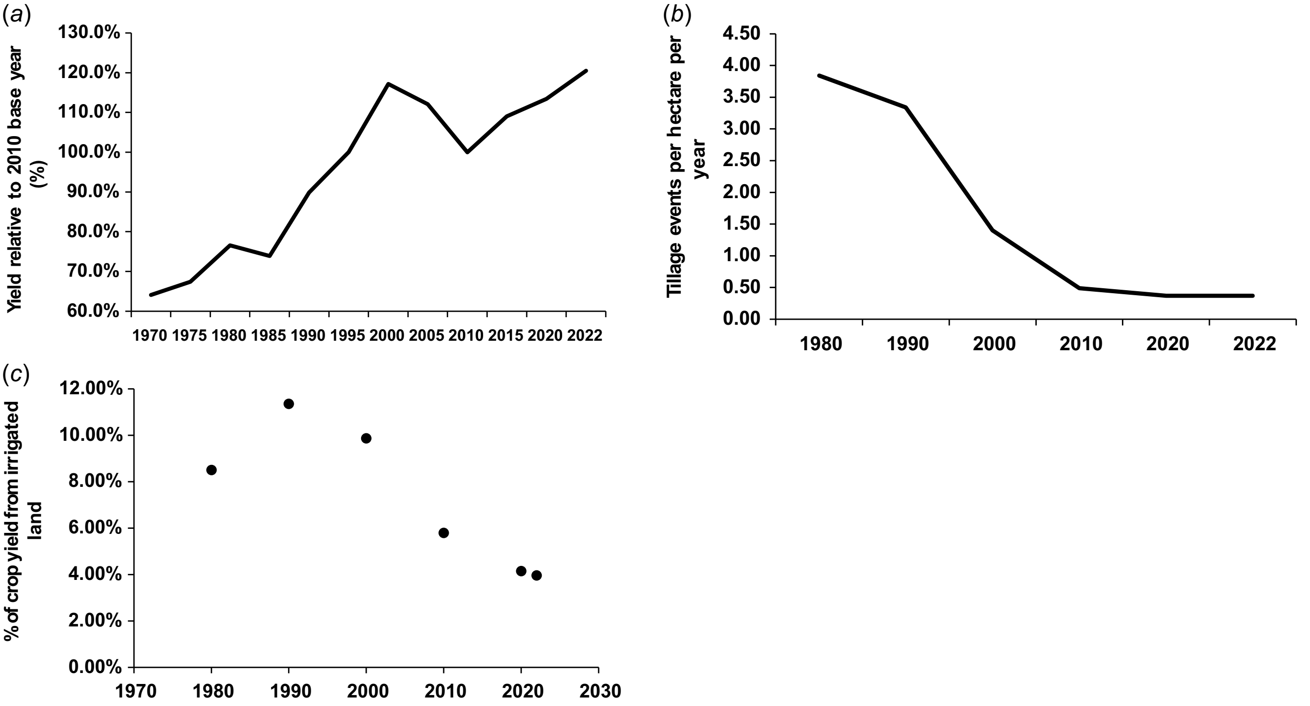

Fig. 8. Changes in grain production systems over the period 1980–2022. (*a*) Historical Australian cereal grains (wheat, barley, and maize) yield relative to 2010 base year in 5-year increments from 1970 to 2020, (*b*) Historical Australian crop tillage events per hectare per year, and (*c*) Percentage of Australian crop yield from irrigated crop land (including supply losses).

Dorca-Preda *et al.* (2021) compared Danish pork production between 2005 and 2016 and determined that GHG emissions excluding LU and dLUC declined over this period (from 2.65 to 2.1 kg CO_2-e/kg LW), and that, although no change was observed in soil carbon, indirect land use change and direct land use change emissions both decreased (from 0.69 to 0.64 and 0.75 to 0.66 kg CO_2-e/kg LW, respectively). Land occupation impacts were also found to have fallen over the decade (4.8–4.4 m^2/kg LW) (Dorca-Preda *et al.* 2021). The reduction in GHG emissions was largely attributable to improvements in productivity and efficiency in crop production (reduced synthetic fertiliser application rates, and lower emission N fertilisers) and feeding, however, emissions from MMS also fell by 18% over the analysis period (Dorca-Preda *et al.* 2021). Bonesmo and Enger (2021) reported a reduction in the carbon footprint of Norwegian finisher pigs from 2.49 kg CO_2-e/kg carcase weight in 2014 to 2.34 kg CO_2-e/kg carcase weight in 2019), driven by genetic and management improvements.

In a trends analysis of the carbon footprint of pork production and consumption in China from 2005 to 2020, Fan *et al.* (2023) reported that improvement in feed technologies, housing and manure management systems facilitated continuous reduction in total industry emissions between 2005 and 2010. More recently, however, industry emissions have increased in response to growing demand for pork (Fan *et al.* 2023), consistent with the findings in this study. The carbon footprint of Chinese pork meat was reported as 3.8 kg CO_2-e/kg carcase weight (Wei *et al.* 2023), considerably lower than the 2022 Australian average reported by Copley *et al.* (2024) of 5.8 kg CO_2-e/kg pork meat; though the study by Wei *et al.* (2023) did not include LU and dLUC emissions, and reported emissions from feed consumption could not be traced back to inventories with disaggregated emission factors.

Vergé *et al.* (2009) compared Canadian pork production from 1981 to 2001 and showed that the GHG emissions (excluding LU and dLUC) decreased by 30% over this period, from 2.99 to 2.31 kg CO_2-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 that resulted in improved herd productivity. Similarly, Boyd *et al.* (2012) reported a decline in carbon footprint for USA pork from 3.8 to 2.5 kg CO_2-e/kg 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.

In comparison, Putman *et al.* (2018) reported a change in the carbon footprint of US pork from 3.34 kg CO_2-e/kg LW in 1960 to 3.08 kg CO_2-e/kg LW in 2015, energy use of 24.17 MJ/kg LW in 1960 to 22.47 in 2015, water use of 0.241 m^3/kg LW in 1960 to 0.180 m^3/kg LW in 2015, and land use from 15.61 m^2/kg LW to 3.77 m^2/kg LW. Although the authors concluded that the complexity of interactions made it difficult to identify specific factors driving improvement, similar conclusions to those made by these authors were reached in the present study. These included that improvement in feed conversion and daily gain contributed to reduction in all impact categories, reduced land occupation impacts were primarily driven by a variety of factors which led to improved crop yields, and that water use results were heavily correlated to irrigation in upstream feed production.

Interestingly, the absolute change in carbon footprint in the present study was much greater than reported in the European (Bonesmo and Enger 2021; Dorca-Preda et al. 2021) and North American (Putman et al. 2018) studies. In addition, although the annual percentage change was lower than Denmark (Dorca-Preda et al. 2021), it was comparable to China (Dai et al. 2021), and higher than for the United States (Putman et al. 2018) and Norway (Bonesmo and Enger 2021). This can be partly explained by 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). 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 freshwater consumption in piggeries, which was found to decline from 30 L/kg LW in 1959 to 18 L/kg LW 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 piggery water consumption from 90 to 28 L/kg LW, with the 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 79% 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 (DCCEEW 2021) 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. 2024) 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 22% (16.7 kg CO_2-e/kg LW to 13.1 kg CO_2-e/kg LW) for Australian beef between the 5 years to 1985 and the 5 years to 2020 (Wiedemann et al. 2023) 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. (2023) 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.

Implications for 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. Although this study revealed a considerable decline across all impact categories, it was also evident that the rate of improvement in carbon footprint and fossil energy demand slowed substantially over the last decade. This is, however, not unique to pork production; the carbon footprint of Australian beef has fallen by 22% since 1980, driven in large part by improved production efficiency (Wiedemann et al. 2024), but the authors identified a slowing in the rate of improvement since 2001 (Wiedemann et al. 2015). Additionally, although complementary reductions in environmental impacts occurred in grain production systems for the first three decades, the industry is yet to develop an emission reduction pathway, meaning that the extent of further future environmental improvement is uncertain. In contrast, further reductions in freshwater consumption were observed in the feed production system across the analysis 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 freshwater consumption. The greatest opportunities exist in further herd productivity improvements, optimised diets, 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. Risks exist from the financial benefits of selling carbon credits to other sectors, which therefore are now able to be claimed against pig industry progress (Copley et al. 2024).

Herd productivity improvements

Although Australian pig herd performance has significantly improved since the 1980s, (OECD/FAO 2022) there is still room for ongoing environmental improvement via herd performance gains from genetic improvements, based on comparison to international data (OECD/FAO 2022). Genetic improvements in growth, reproduction and carcase traits as well a focus on genotype and commercial environment interactions could deliver further reductions in the carbon footprint of piggery operations (McLaren 2007), however, Australia may be constrained by certain commercial limits, e.g. for leanness, which are not present in other jurisdictions.

Increasing the turnoff weight at slaughter is an alternative that 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 emissions per kg of LW produced by 0.4 kg CO_2-e due to reduced feed requirements. That is, increasing turnoff weight of the additional pigs needed to meet increased market demand would have a lower carbon footprint. The GHG emissions from additional pork is significantly lower than the impacts from average pork. Likewise, an Australian beef GHG study showed that imposing more mitigation strategies with the potential to profitably enhance liveweight turnoff allowed a greater reduction in emissions intensity (Harrison *et al.* 2016).

Optimised diets

The optimisation of pig diets through greater digestibility could reduce total feed consumption and nutrient excretion, which could further reduce the environmental footprint of piggery operations in Australia. Additionally, further 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; Patience *et al.* 2015) and reduce the GHG emission associated with manure treatment in uncovered anaerobic ponds. Another common optimisation strategy is reducing dietary CP in pig feed by increasing the inclusion rates of SAAs, reducing the proportion of high protein ingredients in feed, and sourcing low-environmental impact feed ingredients (Meul *et al.* 2012; Ogino *et al.* 2013; Garcia-Launay *et al.* 2014; Trabue *et al.* 2021).

The use of local diet components can significantly reduce the GHG emissions and fossil fuel use associated with 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 (Gustavsson *et al.* 2011; FAO 2013; 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. Although there are logistical and regulatory difficulties (swill feeding) associated with human supply chain pre-consumption food waste, there has been significant uptake by industry between 2010 and 2022, particularly in CAP systems, further reducing the environmental impacts of feed and pig production.

Optimised biogas

Increased uptake of biogas and closed loop technologies has yielded major improved environmental improvements 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. For biogas to be viable at each conventional piggery, one or all of the following would be required: expansion of small-scale conventional piggeries to a size sufficient (>4000 sows farrow-to-finish) to justify the capital cost, conversion of existing conventional and deep litter piggeries to a higher proportion of conventional production, and/or source government or private sector (e.g. customer) funding to subsidise the capital costs.

Limitations

An important limitation of this work is that 1980 and 2000 data were produced from hindcast trends. Prediction of past 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. Although the results do not describe the full environmental consequences of past production, the study revealed a clear trend of improved environmental efficiency. Additionally, this study did not comprehensively assess all nutrient flows associated with pork production. Nutrient flows for Australian pork production have been reported elsewhere, however, first by Wiedemann (2015) for nutrient distribution in outdoor pig production systems and more recently marine and freshwater eutrophication potential for the national herd (and by production system) for 2020 and 2022 by Copley *et al.* (2024).

Although the analysis of LU and dLUC emissions from Australian cropland (and the subsequent impacts for pig feed and per kg of LW) is associated with some uncertainty, the results are nevertheless insightful and represent the first published analysis of historic soil carbon emissions and removals from Australian cropland. More research is needed to understand and improve the granularity of the available data but the macro-level data (coupled with clear trends and records of improved practices in the Australian grain sector) support the conclusion that soil carbon losses from Australian cropland have fallen over the past four decades.

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. 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.

Estimates of improvements in environmental efficiency reflected enhanced herd productivity and changes in management of key resources such as water and land. Over the 42 years since 1980 there has been a 74%, 92%, 61%, 90% and 42% reduction in GHG emissions, LU and dLUC emissions, fossil fuel use, freshwater 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, suggesting industry and government will need to focus and invest in strategies that deliver the next improvements.

Supplementary material

Supplementary material is available online.

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