The low emission future of pork

A consequential life cycle assessment study of Australian pork production

Project 4c-121

Report prepared for the

Co-operative Research Centre for High Integrity Australian Pork

By

Stephen Wiedemann and Kalinda Watson

Integrity Ag Services
36a Highfields Road, Highfields,
Queensland 4352 Australia

May 2018

An Australian Government Initiative

CRC Australia

Pork CRC

CRC for High Integrity Australian Pork

Executive Summary

The Australian pig industry has experienced significant changes in the scale and level of productivity achieved by producers over the last four decades. More recently, benchmarking performed by the Co-operative Research Centre for High Integrity Pork (the Pork CRC) has shown a significant improvement in productivity, with more liveweight (LW) sold per sow, and lower herd feed conversion (HFC). During the period of the Pork CRC, new technology to capture biogas and generate electricity has been developed and implemented in a proportion of the industry. At the beginning of the Pork CRC, the industry established a proactive target to reduce the carbon footprint (CF) of pork production to 1.0 kg CO_2-e kg LW^{-1}. Benchmarking of industry performance in 2010 revealed an industry average CF of 3.6 kg CO_2-e kg LW^{-1}. This benchmarking study also demonstrated that better herd productivity (principally lower HFC) resulted in a lower CF, and that biogas installation and electricity generation on-site could substantially reduce the CF of pork production. The present study was initiated to determine the CF of future, Australian pork production. Three scenarios were modelled investigating increased production from marginal pork suppliers (i.e. piggeries with the greatest potential to expand). Expansion of pork production by 2020/21 was projected to be substantial at the time of initiating the study, and piggeries planning expansions were used to identify the marginal suppliers. Marginal piggeries were found to predominantly utilise conventional housing with biogas capture and energy production to meet on-site electricity demand. A smaller, but significant proportion of marginal suppliers were found to use outdoor-bred and/or deep-litter systems. A survey of these marginal suppliers revealed above average herd productivity levels.

This study revealed that future marginal Australian pork production generated lower CF impacts across three scenarios than benchmarked, average impacts, with impacts approaching the CF of average Australian chicken meat.

The results of the study showed the CF, excluding land use change (LUC) of marginal pork production, was 2.0 kg CO_2-e kg LW^{-1} in 2015/16, declining to 1.3 kg CO_2-e kg LW^{-1} in the 2020/21 scenario. The optimised scenario for 2020/21 had a CF of 1.1 kg CO_2-e kg LW^{-1}. Emissions were also estimated to arise from LUC associated with expansion of soymeal production to meet the increased demand for pig feed, amounting to 1 kg CO_2-e kg LW^{-1} in 2015/16 and 0.95 kg CO_2-e kg LW^{-1} in the 2020/21 scenarios. Improved piggery productivity and a change in the type of housing and manure management resulted in 44% lower impacts for marginal pork production in 2015/16 and 63% lower for 2020/21 compared to 2010, excluding LUC. When the impact of feed production LUC was included, the improvement compared to the 2010 was 23% in 2015/16 and 41% in 2020/21.

Key factors contributing to the substantial improvement in CF for projected, future Australian pork is the change in herd performance and manure management system.

Biogas production was found to be a common feature of the larger, new conventional piggery developments. The cost effectiveness of biogas installation is supported by the market for Australian Carbon Credit Units (ACCUs), which provides a revenue stream from gas used to generate electricity, and excess, flared gas. This has substantially improved the cost-effectiveness of biogas installation in Australia and is a key policy feature assisting the industry transition to lower emissions in the future.

Further research is required to examine a range of options to reduce impacts from high impact diet inputs such as soymeal, and to examine a wider range of environmental impact categories. Preliminary investigations of other options to increase production, such as increasing slaughter weight, also provided promising outcomes, suggesting further opportunities exist from changes to herd structure and productivity levels. Using the established model, industry benefits may be derived from investigating a broader range of options to improve future environmental performance.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ABS	Australian Bureau of Statistics
ACCU	Australian Carbon Credit Unit
aLCA	Attributional LCA
CAP	Covered anaerobic pond
CF	Carbon footprint
CFI	Carbon Farming Initiative
CH_4	Methane
cLCA	Consequential life cycle assessment
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CP	Crude protein
DA	Development approval
ERF	Emissions Reduction Scheme
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Herd feed conversion
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LW	Liveweight
LUC	Land use change
NH_3	Ammonia
N_2O	Nitrous oxide
OECD	The Organisation for Economic Co-operation and Development
Pork CRC	Australia's Pork Cooperative Research Centre
SPU	Standard pig unit
VS	Volatile solids

Acknowledgements

The authors gratefully acknowledge the Australian Pork Cooperative Research Centre for the provision of research funding and academic support. Many thanks also to the piggery managers and industry experts for supplying data. Thanks also to Dr Aaron Simmons (NSW DPI) and Mr Eugene McGahan for technical advice.

Introduction

The demand for food production, and more specifically meat, is predicted to increase in response to increased population and income levels globally, through to 2050 (FAO, 2009). Globally, increasing production is challenged by the limited supply of natural resources and global targets to reduce greenhouse gas (GHG) emissions. The Australian pork industry is faced with a three-fold challenge:

1. increasing production to meet demand,
2. adapting to a changing and increasingly variable economic and natural environment, and lastly,
3. improving its environmental performance and specifically, reducing GHG emissions.

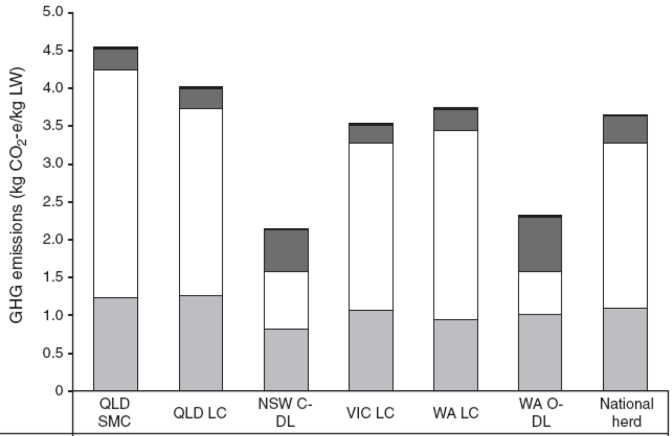
In response to the challenge posed by climate change, the Australian pork industry has established proactive goals to reduce the GHG emission intensity of pork production across the industry, with a goal of targeting emissions of 1.0 kg CO_2-e/kg of pork LW produced. The Australian pork industry, since 2010, has benchmarked emissions using comprehensive, life cycle assessment (LCA) studies of GHG emissions from pork production, with the aim of identifying low emission development pathways for the Australian pork industry.

Emissions from piggeries

There are many sources of GHG emissions throughout the pork production supply chain, including: manure management, emissions generated in the production of feed and other piggery inputs, the use of fossil fuels for feed milling, transport and general farm activities and even emissions generated in the manufacture of infrastructure. The three main GHGs produced are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). MacLeod et al. (2013) in their study of global GHG emissions for pig supply chains reported that feed production contributed 47% of emissions, with an additional 13% related to LUC caused by crop expansion. Emissions related to manure storage and processing accounted for the next largest category, at 27% of the total GHG emissions. Remaining emissions were nitrous oxide, enteric, energy related and post farm emissions (8%).

In an Australian context, the GHG emissions from piggeries vary greatly depending on the type of pork production system used (conventional, deep litter or outdoor) and the manure management systems (MMS) used. In Australia, conventional piggeries typically house pigs within sheds that are regularly flushed, and manure is collected as effluent, which is then treated by either an anaerobic pond or a covered anaerobic pond (CAP) or digester. Deep litter is a housing system in which pigs are housed on litter (typically straw, sawdust or rice hulls) that absorbs manure moisture. After use, the spent litter is then stockpiled or composted prior to land application (aerobic MMS). Outdoor piggeries allow pigs to range in a paddock environment with a shelter, and manure is directly deposited to the paddock. As a result, the manure is handled in an aerobic environment (aerobic MMS). Figure 1 shows GHG emissions of different Australian piggery types from Wiedemann et al. (2016) in their benchmarking research. This study found that emissions from conventional piggeries were higher than for the alternative production systems, in response to the very high methane emissions (averaging 64% of the total GHG emissions) from effluent treatment in open, anaerobic ponds. In contrast, the deep litter and outdoor systems had much lower methane emissions, but relatively higher N_2O emissions. For Australian pork production, the second largest contribution to emissions was from feed production. Electricity consumption and the use of fossil fuels on-site for feed milling, transport and general farm activities also contribute a significant proportion of total GHG emissions (Wiedemann et al. 2016).

Wiedemann et al. (2016) found that average GHG emissions for the national herd, as of 2010, were 3.6 kg CO_2-e/kg LW^{-1}, with the largest determining factor on total emissions being the relative proportion of pigs managed with high or low emission MMSs. This research established a benchmark for the Australian pork industry and provides context for the present research.



	QLD SMC	QLD LC	NSW C-DL	VIC LC	WA LC	WA O-DL	National herd
■ Other minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	0.29	0.25	0.55	0.24	0.28	0.79	0.35
□ CH_4	2.99	2.47	0.75	2.21	2.50	0.50	2.18
CO_2	1.24	1.26	0.83	1.07	0.94	1.01	1.10

Figure 1. Total greenhouse gas emissions (excluding land use (LU) and direct land-use change (LUC) per kilogram of liveweight for six case-study supply chains and the Australian national herd.

(Queensland small-medium conventional (QLD SMC), Queensland large conventional (QLD LC), New South Wales conventional housing (breeding pigs) and deep-litter housing for grower- finisher pigs (NSW C-DL), Victorian large conventional (VIC LC), Western Australian large conventional (WA LC) and Western Australian outdoor housing (breeder pigs) and deep-litter housing for grower-finisher pigs (WA O-DL)

In early Australian pork LCA research, Wiedemann et al. (2010) postulated that significant reductions in GHG could be made by capturing and combusting methane generated from anaerobic lagoons, and by using this methane to generate electricity and/or heat. Since this study was completed, the Australian Government has introduced legislation (the Carbon Farming Initiative, CFI, and later the Emission Reduction Fund, ERF) under which pig farmers are able to claim Australian Carbon Credit Units (ACCUs) for mitigating these emissions. This has significantly increased interest and uptake in technologies to capture and destroy methane and generate energy. Additionally, it has increased the likelihood of these technologies being taken up by the industry, which will result in lower GHG emissions from the average kilogram of Australian pork.

Research by Wiedemann et al. (2011) showed that 62-80% of GHG emissions from conventional piggeries may be reduced by the installation of covered ponds or digesters to capture and destroy methane from effluent ponds, and by using this energy source to generate electricity (Figure 2).

These studies demonstrated the potential for emission mitigation but did not study the impact of increasing uptake across the current industry. The studies have also represented 'snapshots' of the industry in a given year, and have not considered the dynamic changes that have occurred in the industry. Importantly, this history of change in the structure and production levels of the industry indicates the future production may be substantially different to the present. Such dynamic changes must be understood, and taken into account, when determining the future environmental impacts.

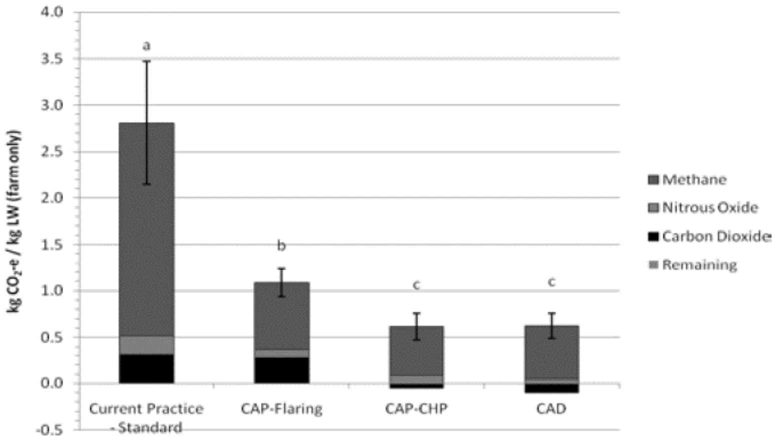


Figure 2. Greenhouse gas emissions from four alternative effluent treatment systems for a simplified piggery system.

The treatment system investigates included: Covered anaerobic ponds (Current Practice - Standard/CAPs) with flaring (CAP-Flaring/CAP-F), combined heat and power generation on-farm (CAP-CHP) and transporting effluent off site for processing at a centralised anaerobic digestion plant (CAD).

The changing production landscape for Australian pork

The structure and productivity of the Australian pork industry has changed substantially over the past four decades, as pig farms have moved from smaller, mixed enterprise operations to larger, more intensive and specialist producers (see Figure 3, Figure 4 and Table 1). Over the same time period, average Australian pork consumption has significantly increased from 12.1 kg per annum in 1973/74 to 27.6 kg per annum in 2015/16 (Figure 5).

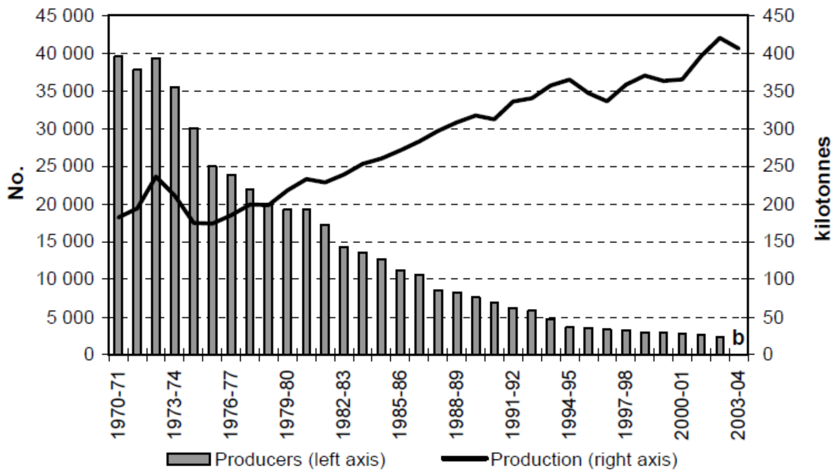


Figure 3. Australian pig producers and pig meat production from 1970-2002 (sourced from the Australian Government Productivity Commission, 2005)

Notes: producer numbers are based on the number of establishments with breeding sows or gilts (intended for breeding). Producer numbers are not available for 2003-04.

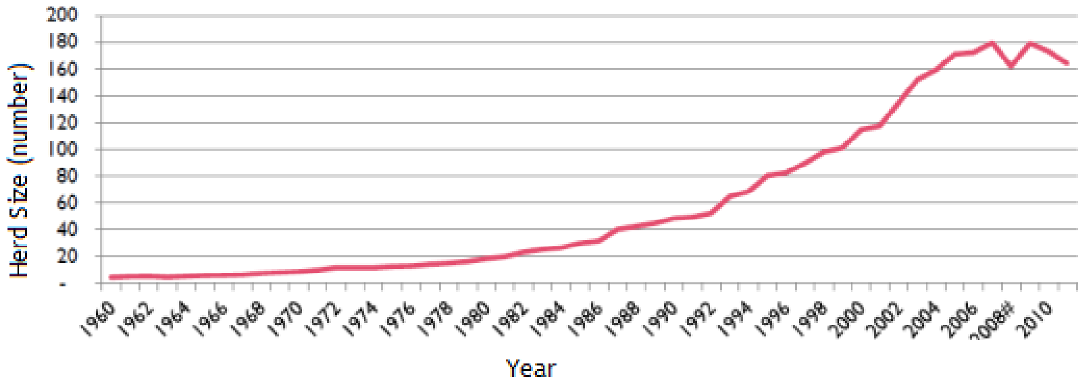


Figure 4. Average herd size for Australian piggeries 1960-2011. (sourced from APL, 2012).

Notes: Producer numbers were not collected in 1974 by ABS or prior to 1969. # From 2008 onwards, numbers of breeding sows only represented.

Table 1. Producer distribution by herd size (sow #) (sourced from PigStats 1993, 2000 and Australian Pig Annual 2011- 2012)

	Year		
Producer distribution by herd size (sow #)	**1990**	**2000**	**2010**
0-49	15.3%	7.5%	3.5%
50-99	15.9%	9.9%	3.0%
100-399	30.0%	24.2%	21.9%
400-999	9.7%	15.2%	9.2%
1000+	29.1%	43.1%	62.3%

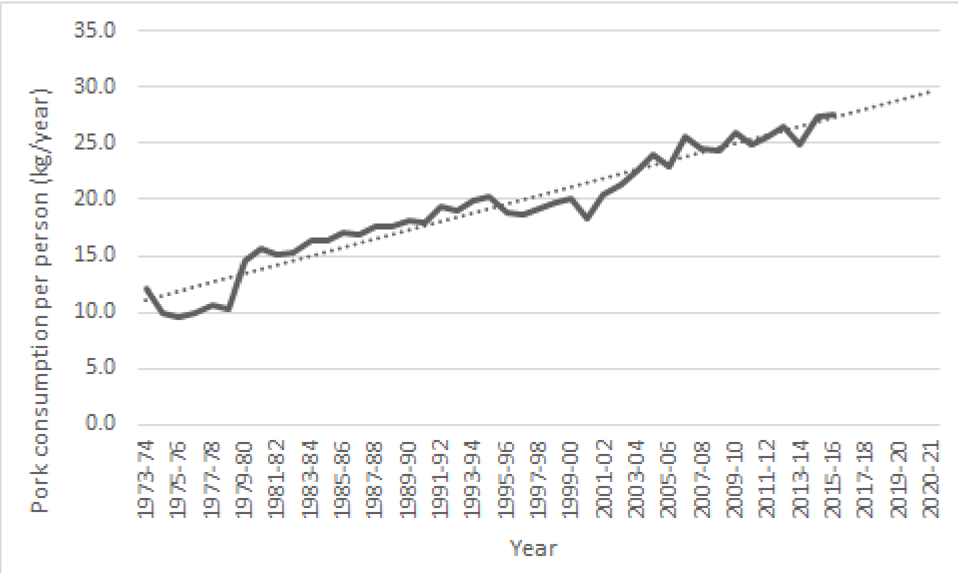


Figure 5. Australian pork consumption per person per year (kg) (ABARES, 2017)

When previous figures and table are analysed together it indicates that the increase in pork production is likely to be derived from the expansion of larger producers because of the stratified industry structure.

The increased pork production was predicted to be 10% above the total 2015/16 production in Australia (Figure 5). This was a conservative estimate based on pork consumption estimates. Specifically, Australian pork consumption was predicated to increase from 27.6 kg/person/year in 2015/16, to 29.2 kg/person/year in 2020/21. When adjusted for likely population increase, this resulted in a 14% increase in pork consumption.

Life cycle assessment

Life cycle assessment (LCA) is a well-established research method that can be used to evaluate the environmental impact of a product, process, or activity throughout its life cycle. The LCA methodology has its own ISO standards (14042/14044) (ISO, 2006a, 2006b).

Studies are conducted in four stages:

i) goal and scope establishment,

ii) data collection (life cycle inventory),

iii) life cycle impact assessment (LCIA), and

iv) interpretation.

The degree of flexibility within the research framework and the specific data collection processes employed allow a considerable degree of variance between studies, and caution must be taken when comparing LCA studies. These elements primarily relate to the goal and scope of the study and the data collection (inventory) approach used.

Summary of pork LCA studies

During the last few years, the number of pork LCA studies has increased. However, these studies vary considerably in their scientific robustness, system boundaries, functional unit, allocation method and emission factors.

Table 2 shows a review of pork LCA studies conducted in OECD countries, showing the Carbon footprint (CF) of pork. CF is expressed in terms of CO_2-e, consisting of greenhouse gas emissions of CO_2, CH_4, and N_2O, which are calculated using equivalence factors. The CF of other OECD countries with similar production systems ranges from 1.45 to 10 kg CO_2-e per functional unit produced. However, the variation in system boundaries and use of different methods limits the comparison between different LCAs.

Table 2. Carbon footprint results from pork LCA studies conducted in OECD countries

Reference	Country	LCA method	Functional unit	System boundaries	Results (CF*, kg CO_2-e per kg of product)
Dalgaard et al. (2007)	Denmark	Consequential	1 kg of pork delivered to the Port of Harwich (carcass weight)	From feed production to transport of pork to the Port of Harwich	3.6
Nguyen et al. (2011)	Denmark	Attributional and consequential	1 kg of pork delivered from slaughterhouse (carcass weight)	From feed production to the delivery after slaughtering	3.1-3.4
Van Zanten et al. (2018)	Netherlands	Attributional and consequential	1 kg of live weight gain	From feed production to the farm gate	1.45-1.67
Halberg et al. (2007)	Denmark	Attributional	Per kg LW	From feed production to the farm gate	2.8-3.3
de Vries and de Boer (2010)	Netherlands	n/a	Per kg LW	Review	3.9-10
Hirschfeld et al. (2008)	Germany	Attributional	1 kg of pork (carcass weight)	From pre-production, feed production to the farm gate	3.1
Reckmann et al. (2013)	Germany	Attributional	1 kg of pork (for total pork production)	From feed production to the farm gate	3.22
Basset-Mens and van der Werf (2005)	France	Attributional	1 kg of pig produced	From feed production to slaughtering	2.3-3.9
Williams et al. (2006)	Great Britain	Attributional	1000 kg of pig carcass	From feed production to the farm gate	6400
Lamnatou et al. (2016)	Spain	Attributional	1 kg of meat (live or carcass weight)	From feed production to the farm gate	3.2-5.5
Baumgartner et al. (2008)	Spain	Attributional	1 kg of pork LW	From feed production to	3.78 -3.85

				the farm gate	
Noya et al. (2017)	Spain	Attributional	100 kg LW at farm gate	From feed production to the farm gate	3.4
González-García et al. (2015)	Portugal	Attributional	1 kg of meat (carcass weight)	From pre-production, feed production to slaughtering	3.34
Reckmann et al. (2012)	Europe	n/a	1 kg of pork (carcass weight)	Review study	3.6
Wiedemann et al. (2016)	Australia	Attributional	1 kg LW	From feed production to the farm gate	2.1-4.5 (case study farms) 3.6 (national average)

* CF: carbon footprint. Note functional units are different and therefore results are not directly comparable. See Table 8 for results from comparable studies with harmonised functional units.

Consequential and attributional LCA

There are two basic perspectives that an LCA study can use. Many earlier LCAs, including those for the Australian pork industry, were done retrospectively. This is termed an attributional LCA, because the impacts are *attributed* to the product being investigated. The main question for an attributional LCA is “What impacts were generated by producing this product?” If a study is investigating production for a whole state or nation, every type of system that is currently being used needs to be included to get an accurate and representative result.

An alternative approach is to consider a dynamic system and investigate the consequences of a change in production. In this case the question might be “What impacts would be created if one more unit of product were produced?” This is termed a consequential LCA (cLCA). Activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand in this modelling approach. Hence, cLCA concentrates on micro-economic actions strongly connected to macro-economic consequences, by identifying the marginal suppliers and/or marginal technologies likely to be affected by changes in the demand of a product. A consequential study is focused on the technologies/processes ***actually affected***, i.e. the system that would be used if the industry expanded (Weidema, 2003). This is quite an important distinction which may lead to different results to an aLCA, as aLCA is static, context independent, and average. While cLCA is dynamic, context specific, and marginal.

Consequential LCA has been used for environmental assessment of milk production (Chobtang et al, 2016, Cederberg, 1998, Thomassen et al, 2008), pork (Dalgaard et al., 2007), beef (Cederberg and Stadig, 2003), grains (Vázquez-Rowe, 2013), plant proteins (Dalgaard et al., 2008, Schmidt and Weidema, 2008), biofuels (Tonini et al., 2012) and other agricultural/horticultural products (Thrane, 2006, Samuel-Fitwi et al., 2013, Reinhard and Zah, 2009).

cLCA and system expansion

Commonly in agricultural systems, processes are shared between several production systems, so it is uncertain to which product the environmental impacts should be assigned. Allocation between products, typically using either biophysical or economic relationships, is the preferred method in aLCA. However, the International Organisation for Standardisation (ISO, 2006a) recommends using subdivision or system expansion methods, which is usually only applied in cLCA. Weidema (2003) developed a specific methodological procedure for applying system expansion to model the consequences of a product substitution on a co-producing system. When applying system expansion, all inputs and outputs are entirely ascribed to the product of interest. Subsequently, the product system is expanded to also include the products avoided, i.e., products that are avoided due to the co-products of main products produced or used. An example of this can be provided from the case of protein meal production.

Soybeans are grown in many regions of the world as a grain protein. When soybeans are processed, soymeal is produced, and soybean oil is a co-product. Increased demand for soybean meal leads to increased production of soybean oil. To handle the subdivision of impacts between the two products, the oil product is substituted for a vegetable oil from a crop predominantly grown for oil. In this case, canola is a suitable substitution because it is a global marginal vegetable oil product. However, this substitution induces a second change, namely, that when less canola oil is produced, less canola meal is also produced. A second substitution is then carried out to account for this reduced canola meal, thus providing two processes, one producing marginal protein meal (soymeal) and the second producing marginal vegetable oil (canola oil).

cLCA and marginal suppliers

In LCA terms, a marginal supplier (sometimes termed an affected supplier) is a producer that is actually affected by a change in market demand (Schmidt 2007, Weidema et al 1999). That is, marginal suppliers are able to increase or decrease their supply in response to an increase or decrease in demand for their product. Marginal suppliers in cLCA models are identified using a 5-step procedure (Weidema, 2003), shown in Figure 6. During the market delimitation step, the boundaries of the study, possible production constraints on the ability of suppliers to respond to the change, and suppliers that will actually be affected by the change (i.e. the most sensitive) are identified. If the general trend of a market is expanding or stable, a long-term change in demand is assumed to affect the most competitive supplier that has the best options for expanding or renewing the production capacity. However, if the general trend of the market is rapidly decreasing, reducing production capacity, a change in demand is assumed to affect the least competitive supplier (Reinhard et al., 2010). Furthermore, sometimes suppliers are constrained in their ability to respond to a market change. For example, in a decreasing market a pork producer may have a production contract that they must meet, so they cannot decrease pigs produced in response to cost pressures or a decrease in market demand. Thus, in addition to being able to repose to a market change, a marginal supplier must not be constrained (Reinhard et al., 2010). In order to identify the marginal suppliers (i.e. the most or least competitive, un-constrained suppliers) it is necessary to have information about:

- the market being investigated: Including the products and co-products, market trends, supplier trends, and the geographical and temporal boundaries of the market,
- the market constraints: In general, we assume that suppliers are not constrained unless there is evidence to the contrary, and the
- competitiveness of different suppliers: Represented by their production costs and market share.

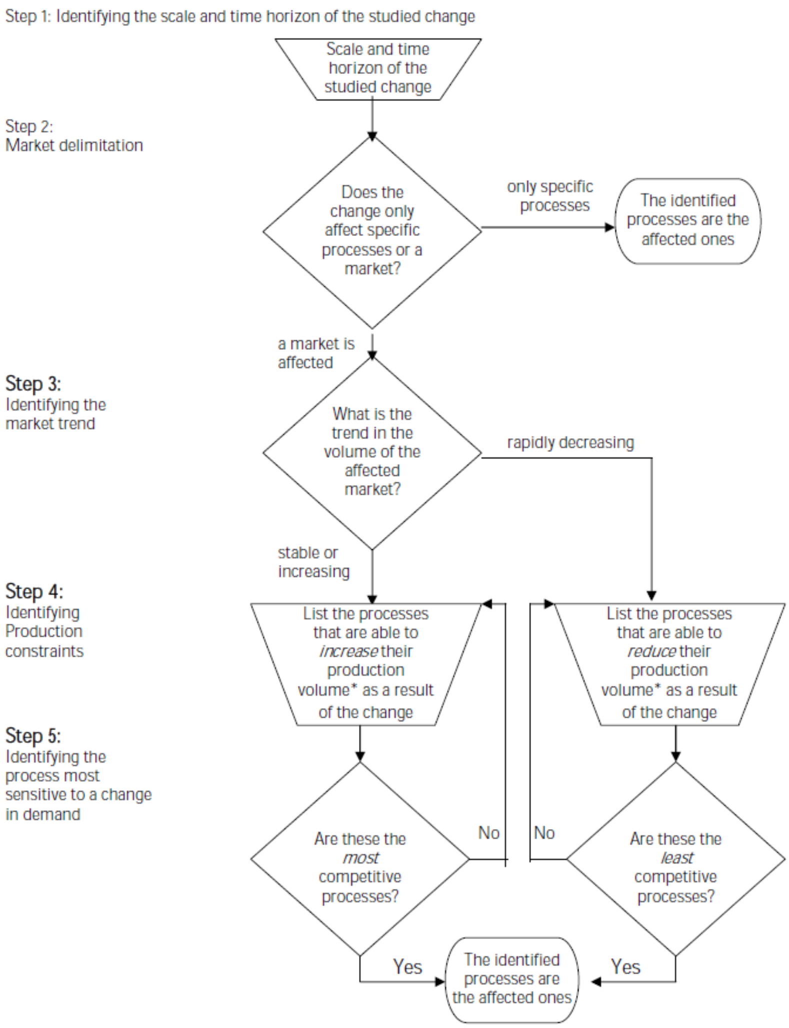


Figure 6. Decision tree outlining the 5-step procedure for identifying the processes affected by a change in demand for a specific intermediate product (Weidema, 2003).

The specific method choices made in the study regarding marginal suppliers are outlined in the following sections.

Methodology

Goal and scope

Through consultation with the industry, the following project aims (goals) were identified:

1. To quantify the GHG impacts from marginal suppliers of Australian pork.
2. To provide LCA data on Australian marginal suppliers and demonstrate an application of consequential LCA modelling.
3. To assess GHG emission trends of marginal suppliers in 2015/16 and projections of the GHG emission impacts from the pork industry in 2020/21.

The target audience for this research includes the pork industry, pork producers and researchers. We note that this study is not a full “cradle-to-grave” LCA (the end point is the farm gate). For this reason, the results are not able to inform consumers of the full impacts of consuming pork. The study focused on CF, measured in CO_2-e using IPCC (Solomon et al. 2007) Global Warming Potentials (GWPs). GHG emissions associated with LUC were included and reported separately, following guidance from the Livestock Environmental Assessment and Performance partnership (LEAP, 2014). Modelling was undertaken using SimaPro 8.5 (Pré-Consultants, 2018).

Functional units and system boundaries

The study covered the primary production supply chain from breeding through to finishing, including all processes required to produce pigs ready for transport to meat processing. The reference flow (analogous to a functional unit) was one kilogram of ***'additional'*** pork LW at the farm gate. A 10% increase in demand was assumed, based on the rising demand for domestic pork.

Datasets and processes used to define marginal producers

A customised cLCA database was developed to predict emissions from background processes and pig production. As Figure 7 shows, performance data for the LCA models came from three sources. Performance data from the baseline study (2010/11), inventory data collected from marginal producers for 2015/2016, and marginal suppliers identified from industry benchmarking datasets (Pork CRC, 2017). Production trends between 2010-2017 were used to predict piggery performance in 2020.

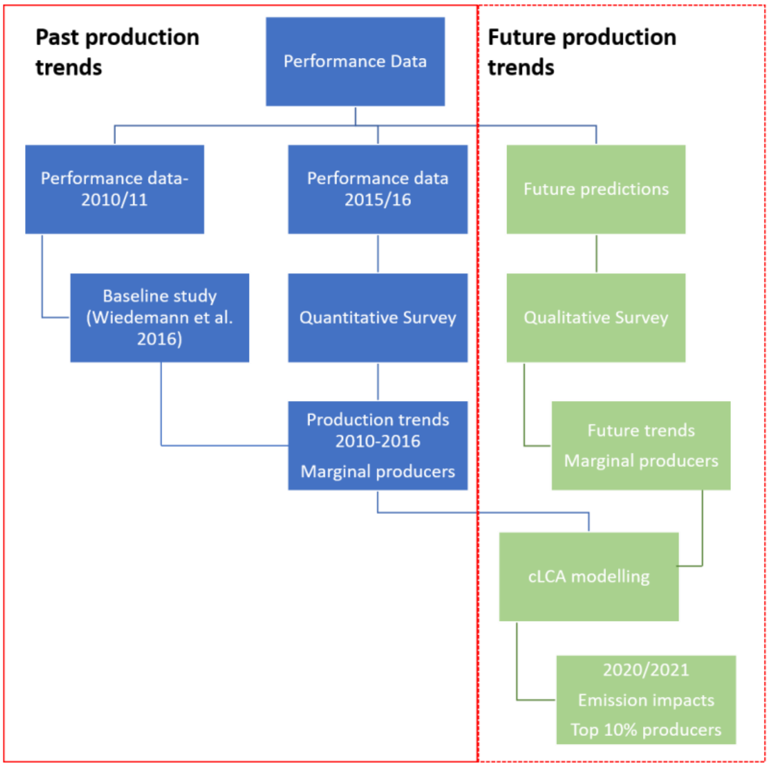


Figure 7. Structure of the study and data sources

The process to identify marginal suppliers followed the Weidema (2003) 5-step procedure, shown in Figure 6. These steps are outlined as follows:

- Step 1 – scale and time horizon. For the present study, 2020/21 was the time horizon, and the scale was a 10% increase in production industry wide.
- Step 2 - market boundary. This study focused on the domestic Australian pork market. Australia is only a minor exporter of pork, and almost all local production is focused on the domestic, fresh pork market.
- Step 3 - define the volume changes of the Australian pork production market. The trend of increasing pork consumption in Australia was identified from the ABARES (2017) Agricultural commodity statistic report (Figure 5). This confirmed the scale of production increase required.
- Step 4 is to define the supplier with the capacity of providing demand adjustment. The proposed marginal suppliers represent those producers that are not constrained and can increase their production to meet market demand.
- Step 5 is to define the supplier with the preferred technology based on the demand. Preferred technology relates to efficiency (and cost) of production and can relate also to market preferences such as supply of outdoor bred pigs.

A novel approach was applied to define producers that met the criteria for Step 4 and 5. Industry consultants, industry experts, local and state Government agencies were surveyed to develop a list of proposed piggery developments in each state of Australia. This survey identified 26 new or expanding piggery developments that had been lodged to receive a development approval in the five years prior to 2017. Considering the construction of a piggery is a long-term project, most of these developments, if approved and constructed, would begin producing pigs in around 2019/20, matching the time horizon for the study. While not all development approvals will move to construction and some developments are speculative in nature, this approach did provide a method for determining those enterprises with the intent to develop a new piggery or expand an existing piggery, and the willingness to invest in formally beginning the process.

Based on the documented development application material (which was typically available from local councils or state regulation bodies because development documents are released for public comment), a profile of the development was constructed. This typically provided information regarding the herd size for the operation, projected output (total production) and feed requirements. Housing type and manure management system, including installation of biogas infrastructure, was also provided as these are key aspects required to issue an environmental licence for a new development. Table 3 shows the type, proportion and average size of the piggeries proposed for development, Australia wide. The total combined size of the developments was 476,846 SPU, approximately equivalent to an additional 48,000 sows, representing an increase of approximately 17% in the Australian herd, based on sow numbers. Figure 8 displays the distribution of piggery development size in relation to the type of piggery, showing the skewed distribution in piggery size, with a small number of large developments contributing the most to the predicted expansion.

The majority of new or expanding piggeries were owned by an enterprise that currently produced pigs, and it was therefore possible to also define the characteristics of the existing operations. From a proportion of these operations, detailed information regarding diet, herd performance and energy use was collected.

Table 3. New and expanded piggery developments showing the proportion of piggeries by major housing and manure management system type and the average piggery development size

Type of piggery	Percent of total expansion	Average size of piggery development (SPU)
Conventional	76%	25,182
Conventional + deep litter	19%	8,835
Rotational Outdoor piggery	5%	2,122

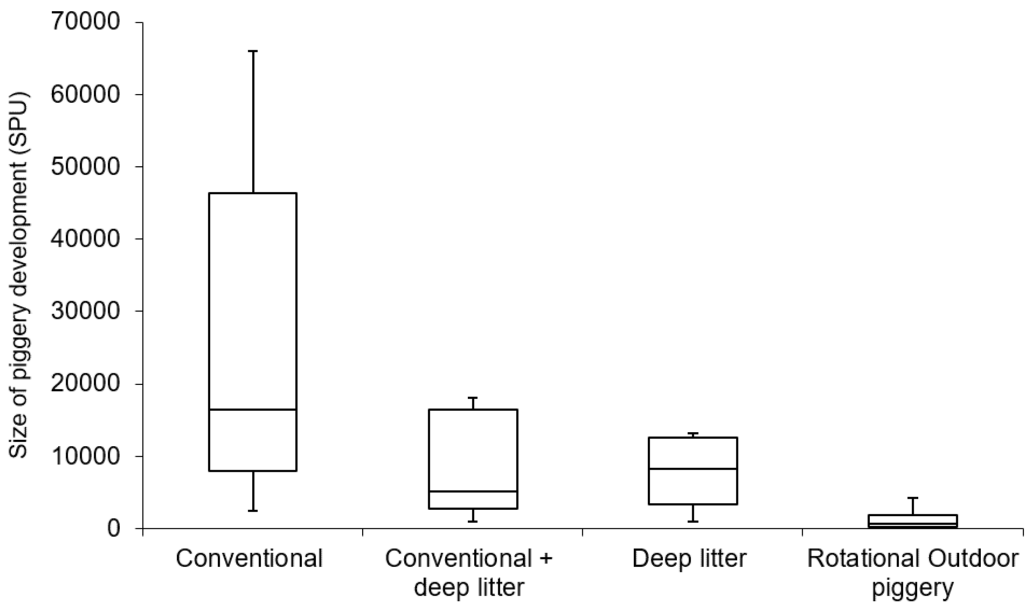


Figure 8.Distribution of piggery development size in relation to the type of piggery

Marginal pork production inventory data

The primary assumptions and methods applied in collating the Life Cycle Inventory (LCI) are reported in this section. Herd inventory data were collated for farrow-finish supply chains in three configurations, outdoor bred, deep litter (wean-finish), conventional breeding, deep litter (wean-finish) or conventional (farrow-finish). Herd productivity data was deemed to be the same for conventional + deep litter and conventional (farrow-finish) and are not disaggregated in Table 4. Diets were assumed to have the same proportions of grain across all piggery system types but were modelled separately between major production regions (see Table 5). Background inventory data are reported in Appendix 1 and Appendix 2 respectively.

Table 4. Piggery herd production and purchased input data for the national marginal production system

Parameter	**Scenario**	Outdoor + Deep litter		Conventional and Conventional + Deep litter	
Year	Unit	2015/16	2020/21	2015/16	2020/21
Litters/sow.year	#	2.3	2.3	2.31	2.31
Pigs weaned/sow.year	#	18.1	19.0	24.5	25.8
No. of sows	#	849	849	1757	1757
Sow mortality rate	%	5.8	5.8	8.8	8.8
Sow culling rate	%	48.5	48.5	52.3	52.3
Average sale weight of slaughter pigs	kg	99.7	99.7	99.7	99.7
Average carcase weight of slaughter pigs	kg	75.7	75.7	75.7	75.7
HFC [a] (grower-finisher)	HFC	1.90	1.90	1.77	1.74
HFC (whole herd)	HFC	3.28	3.27	2.84	2.69

[a] *Herd feed conversion*

Grain inventory data

Grain inventory data were developed by the author in previous studies (Wiedemann & McGahan 2011, Wiedemann et al. 2017a, Wiedemann et al. 2017b) and these datasets were used as an initial dataset for the present study. Piggery diets vary significantly between regions in Australia (Wiedemann et al. 2016) leading to differences in environmental impacts from feed production. In all regions, wheat and barley are major cereal grains, and animal by-product meals are important dietary protein inputs. Different grain proteins are used in different states, with higher proportions of soymeal found in Queensland and NSW diets, and higher proportions of field peas (SA) and lupins (WA) found in other states. In Queensland, sorghum was also considered a marginal summer crop.

According to cLCI methods, only marginal grains (i.e. those with the capacity to increase supply in response to demand) were modelled, resulting in a simplified diet for each state. To achieve this, all cereals and protein meals were substituted for marginal, primary products based on world trade. By-products substituted with the first primary product that could be considered nutritionally equivalent in terms of energy and protein (a summary of primary products is provided in Table 9, Appendix 1). Diets were then re formulated to develop a simplified ration with similar dietary properties in terms of crude protein and energy. It is acknowledged that a degree of inaccuracy is introduced by using this approach, as not all grain sources have a similar amino acid profile or energy content. However, the error associated with this assumption, in terms of carbon footprint, was not expected to be large.

Marginal wheat was assumed to be derived from expansion in Australian wheat production, by increasing fertiliser inputs to increase yields (intensification, see NSW DPI, 2018). Australia is a major global exporter of grain with steadily increasing production over time and is therefore a global marginal production system. The marginal protein meal was determined on a regional basis and was either lupins, field pea or soymeal depending on the region. Marginal soybean was assumed to be derived from a global market (EcoInvent consequential database), while marginal field pea and lupins were assumed to be derived from a domestic market because Australia is a marginal supplier of these grains and modelled by the author.

Table 5. Simplified marginal diets per tonne of ration for four regions in the national marginal production system.

Rations were aggregated across the multiple diets used by farrow-finish piggeries.

Ration component (kg)	NSW-Vic.			Qld			WA			SA		
	B	W	G-F	B	W	G-F	B	W	G-F	B	W	G-F
Wheat	836.3	695.1	762.0	471.2	529.5	490.9	809.8	734.6	802.0	749.8	500.0	659.0
Sorghum	0.0	0.0	0.0	380.7	239.5	350.0	0.0	0.0	0.0	0.0	0.0	0.0
Soymeal	68.7	140.3	107.0	96.2	200.4	139.0	0.0	0.0	0.0	0.0	0.0	0.0
Field pea	62.5	134.6	109.0	0.0	0.0	0.0	0.0	0.0	0.0	213.3	460.5	311.9
Lupins	0.0	0.0	0.0	0.0	0.0	0.0	153.3	225.0	181.9	0.0	0.0	0.0
Canola oil	10.0	9.0	1.0	8.9	13.5	1.5	11.9	21.5	10.0	11.9	11.3	11.0
Low-cost additives	12.5	7.0	14.2	29.0	5.6	12.8	15.5	7.0	1.0	15.5	6.8	10.0
High-cost additives	10.0	14.0	6.8	14.0	11.5	5.8	9.5	11.9	5.1	9.5	21.4	8.1
Total (kg)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Diet digestibility (%)	88.2	89.2	88.9	88.1	89.9	89.00	88.0	88.0	88.6	87.6	87.8	88.2
Crude protein (%)	14.4	18.8	17.1	14.3	19.4	16.1	15.0	17.2	16.0	14.2	17.9	15.7

Transport distances and feed milling inputs were assumed to be the same for the marginal piggeries as for the national average data reported by Wiedemann et al. (2016) and these data (see Appendix 1, Table 10) were applied in the current study.

Manure management emissions and biogas production

Housing type and manure management system inventory data for the marginal piggeries in each state are reported in Table 6, based on the survey of planned piggery developments. Housing and manure management in 2015/16 represent the 'current practice' for the piggeries that have the capacity and intent to expand, while the values for 2020/21 represent the housing and manure management for the proposed developments that are to be constructed.

Table 6. Percent of total piggery expansion and new developments by state for 2015/16 and 2020/21

Type of piggery	QLD	NSW	VIC	SA	WA	Aust.
			2015/16			
Conventional – open anaerobic pond	12.7%	6.0%	3.7%	1.3%	13.3%	37%
Conventional – CAP/Digester	25.6%	6.0%	7.0%	0.0%	0.0%	39%
Deep litter	1.5%	2.4%	6.8%	2.9%	5.7%	19%
Outdoor	0.4%	0.0%	2.3%	0.0%	2.4%	5%
Total	40.2%	14.4%	19.8%	4.2%	21.4%	100%
			2020/21			
Conventional – open anaerobic pond	5.8%	1.0%	3.7%	1.3%	0.1%	12%
Conventional – CAP/Digester	32.4%	11.0%	7.0%	0.0%	13.2%	64%
Deep litter	1.6%	2.4%	6.8%	2.9%	5.7%	19%
Outdoor	0.4%	0.0%	2.3%	0.0%	2.4%	5%
Total	40.2%	14.4%	19.8%	4.2%	21.4%	100%

Manure emissions were determined using the emission factors outlined in the Australian NIR (Commonwealth of Australia, 2016), with the key factors shown in Appendix 3, Table 14. These factors are governed by biological processes and therefore were not altered for future scenarios.

Manure excretion was predicted using methods consistent with PigBal (Skerman et al. 2015). Briefly, the PigBal model uses a mass-balance approach to predict excreted nitrogen, and the dry matter digestibility approximation of manure production method to determine excreted volatile solids. These predictions are based on feed properties and pig herd data, as outlined in Table 4 and Table 5.

Biogas production was modelled with an assumed 0.4 m^3 biogas per kilogram of VS and 70% methane content in biogas. An assumed 10% methane leakage rate was assumed, based on the Commonwealth of Australia (2016). Assumptions used for modelling electricity production are shown in Appendix 3, Table 15.

System expansion and substitution processes

System expansion was applied to multifunctional processes that had more than one functional flow. That is, the avoided environmental impacts of co-products and displaced products are included in the assessment.

In the present assessment, pork from prime (young) pigs and cull breeding pigs was not separated into primary products and co-products, because the end product from both classes of pigs (pork) enters the same general market. Functional differences relate to consumer preferences but not nutritional quality. Therefore, the output from all systems was taken to be total pork produced from all classes of saleable pigs.

Nutrients in manure and effluent was handled using system expansion and substitution, with the replacement products assumed to be synthetic fertilisers. Wiedemann et al. (2010) suggested that nutrients present in sludge, effluent or spent litter cannot be considered directly transferable on a kilogram basis with nitrogen or phosphorus fertilisers. The main reason for this was that nutrients contained manure is typically in a form that is less available for plant uptake. Additionally, 20-30% of nitrogen is typically lost during application (Rotz, 2004) unless manure is rapidly incorporated or irrigated to wash the readily available ammonium nitrogen into the soil. The loss rate from fertiliser nitrogen is likely to be lower than this, particularly if it is banded in the soil. To account for this, equivalence factors were developed and applied in the present study, according to Table 7.

Table 7. Piggery nutrient substitution ratios with fertiliser products

	Substitution product	Piggery sludge / spent litter	Piggery effluent
Nitrogen	1 kg of nitrogen as urea	0.5	0.8
Phosphorus	1 kg of phosphorus as superphosphate	0.7	0.7
Potassium	1 kg of potassium as potassium chloride	0.9	0.9

Electricity generated from biogas and exported from the piggery site was also a co-product in the optimised scenario, after on-site energy requirements were met. This was substituted for the average electricity supply in the state in which the electricity was produced.

Within the background cropping systems, a series of co-products are produced. Specifically, protein meals and oils are typically co-produced, and these were handled by performing a system expansion to handle the co-product from the system. This is explained for the specific crops in Appendix 1. Arguably, straw could also be considered a co-product of grain production but in the majority of cropping systems in Australia it is a residual that is returned to the soil. In the present study, straw was assumed to be a residual, and cereal grains were therefore modelled as having only one product.

Scenario modelling

Scenarios

Three scenarios were developed examine the change in GHG emissions from pork production with current and future marginal suppliers, and the potential total benefit achievable with best practice Australian pork production strategies. These are outlined as follows:

1. *Scenario 1: 2015/16 marginal pork producers with current performance and management*

This was determined from producers in 2015/16 that were classified as marginal based on the criteria outlined in the methods section. Production data, diets and manure management systems were based on 2015/16 management practices.

2. *Scenario 2: 2020/21 marginal pork producers with projected performance and management*

Marginal producers were determined using the criteria and approach outlined in the methods section, based on a survey of piggery development application (DA) submissions surveyed, and the performance of marginal piggeries determined by survey.

3. *Scenario 3: Marginal pork producers with best technology for low CF*

This scenario utilised the same datasets and assumptions as outlined in scenario 2, with peak biogas and electricity production assumed. This was 90% of marginal, conventional piggeries using biogas with electricity and heat production and export to the grid.

Outcomes

Results

Marginal pork producers were found to have improved herd performance, and more frequently utilised biogas systems than the average baseline in 2010. Outdoor bred systems were represented at a higher rate than the baseline, though deep litter represented a slightly smaller proportion of the herd than the national average. Application of marginal diets resulted in considerably fewer feed ingredients after by-products were substituted for primary cereals and protein grains. Between the 2015/16 and 2020/21 scenarios, herd performance was assumed to improve incrementally, while the most significant change was an increased proportion of conventional piggeries with biogas systems installed. This reflected the high proportion of new, greenfield piggery developments that included biogas capture as part of the facility design.

The carbon footprint (CF, excl. LUC) of marginal pork production was 2.0 kg CO_2-e kg LW^{-1} in 2015/16, declining to 1.3 kg CO_2-e kg LW^{-1} in 2020/21. The optimised scenario for 2020/21 had a CF of 1.1 kg CO_2-e kg LW^{-1}. Impacts from the 2015/16 were dominated by manure management emissions (predominantly methane) reflecting the higher proportion of marginal producers that had not adopted biogas systems. However, this declined substantially in the 2020/21 scenario, where more piggeries proposed using biogas systems.

In contrast to previous benchmarking results, the emission profile for the 2020/21 scenarios was more evenly distributed between different gaseous emissions and emission sources. Methane from effluent treatment at conventional piggeries contributed 36%, while carbon dioxide from fossil fuel use contributed 31-36% (see Figure 9). Emissions were highest from the conventional piggeries without biogas, which were typically smaller piggery developments (<1000 sows) where economies of scale made biogas installation less cost effective. Outdoor-bred, deep-litter grower-finisher systems were found to produce low CF pork compared to either the conventional and deep-litter or the conventional systems without biogas. However, emissions were lowest from the conventional production systems with biogas production. The optimised 2020/21 scenario reduced the CF by 15% when compared to the 2020/21 scenario in response to the slightly higher biogas estimates, and modelling excess electricity as being exported to the grid to replace fossil fuel energy.

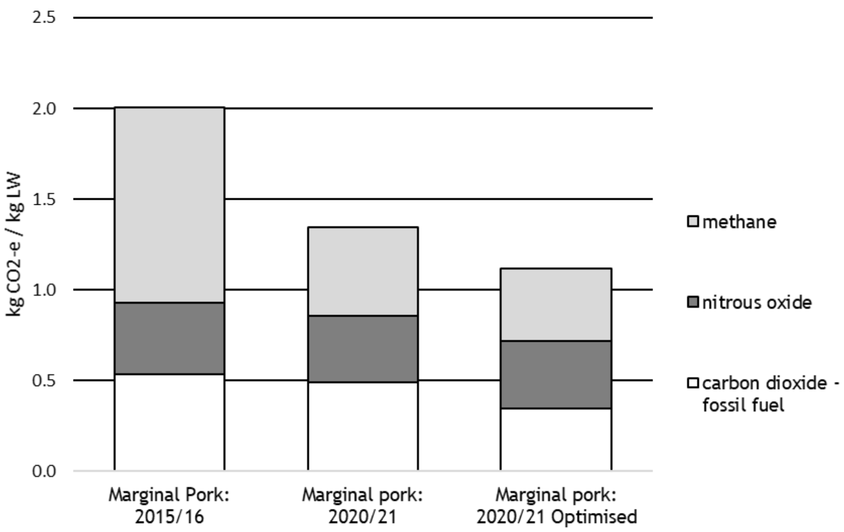


Figure 9. Carbon footprint of marginal Australian pork production with three scenarios

Emissions were also estimated to arise from LUC associated with expansion of soymeal production to meet the increased demand for pig feed, amounting to 1 kg CO_2-e kg LW^{-1} in 2015/16 and 0.95 kg CO_2-e kg LW^{-1} in the 2020/21 scenarios (Figure 10). This large contribution resulted from the projected demand for soymeal in Queensland and NSW, where fewer alternative, marginal protein grains were available. The global marginal soymeal is dominated by South American production, where land use change from pasture to cropland for soy production is common, contributing to very high impacts for this product.

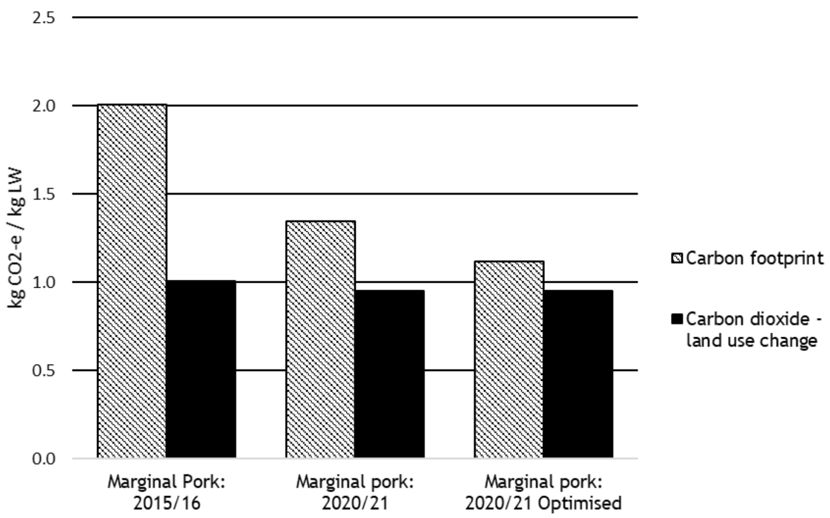


Figure 10. Carbon footprint and carbon dioxide from land use change associated with marginal Australian pork production in three scenarios

Discussion

This study aimed to assess the environmental impacts associated with increased pork production though current industry expansion trend and best technology for low GHG emissions using cLCA. As such, this study only investigated the environmental impacts associated with additional marginal pork production and relevant displaced systems.

Comparison to other studies

LCA studies vary considerably in the system boundaries and technical aspects which makes comparison difficult. In accordance to Noya et al. (2017) only those LCA studies that investigated similar growing systems, production stages, functional unit and allocation methods (system expansion) were identified to be appropriate for comparison with the present study. The CF values range from 2.0 (present study) to 3.42 kg CO_2-e per kg LW^{-1} (Noya et al., 2017), with an average of 2.60 (±0.46) kg of CO_2-e kg LW^{-1}. Results from the present study were lower than the average of studies found in the literature, with differences being primarily related to the lower impact of Australian grain production.

Table 8. Carbon footprint results for Australian and European pork production in comparative LCA studies

Study	Country	Carbon Footprint (Corrected [a]) kg CO_2-e kg LW^{-1}
This study (2015/16)	Australia – 2015/16	2.0 (3.0 with LUC impacts included)
Dalgaard et al. (2007)	Demark	2.57
Nguyen et al. (2011)	Denmark	2.52
Noya et al. 2017	Spain	3.42
Reckmann et al. (2013)	Germany	2.99
Van Zanten et al. (2015)	Netherlands	2.50
Groen et al. (2016)	Netherlands	2.61
Dourmad et al. (2014)	Denmark, Netherlands, Spain, France and Germany	2.25

[a] LW and carcase weight converted using a dressing percentage of 78%

Table adapted from Noya et al. (2017).

Results corrected per kg liveweight of pig from a cradle-to-gate farm perspective.

Studies applying the same consequential modelling approach have not been conducted for other Australian meat products. Impacts from pork production from the 2020/21 scenarios in the present study were similar to the average (aLCA) impacts from Australian meat chicken production reported by Wiedemann et al. (2017b). Noting that the latter study was an analysis of average production using aLCA methods, it is likely that marginal Australian chicken would be produced with lower impacts than this suggests because of better feed conversion ratios and the use of marginal diets and energy supply though LUC impacts may also be substantial for marginal chicken meat. None-the-less, the result is significant and demonstrates that marginal Australian pork has far lower impacts than industry averages might suggest, reducing the difference between marginal pork production and average of chicken production systems.

Feed and LUC

Impacts were found to be substantial from feed production. In the 2015/16 scenario 41% of the CF was associated with feed production, and this rose to 61-70% in the 2020/21 scenarios, though in absolute terms impacts decreased slightly in 2020/21 because of better HFC. Feed impacts arise from field operations, fertiliser emissions, transport and milling and are typically a major impact area for pork production. This high contribution associated with feed production was similar to previous (Reckmann et al., 2016, Basset-Mens and van der Werf, 2005; Dalgaard et al., 2007; Nguyen et al., 2011; Reckmann et al., 2013; Gonzalez-García et al., 2015; Lamnatou et al., 2016).

Impacts from LUC also arise via the feed system, principally from protein meal production. Globally soymeal is the marginal, traded protein meal, and increases in demand for protein meal in Australia has resulted in an increase in imported soybeans for use in Australian animal diets (FGP, 2016).

Global increase in demand for soymeal has resulted in expansion in soybean production in South America, primarily by expanding the area used for crop land, has resulted in land transformation from grassland or forest (deforestation) resulting in substantial LUC carbon losses (Cherubini et al., 2015, Barona et al. 2010, LEAP, 2014, Fehlenberg et al. 2017, Castanheira and Freire, 2013).

When the impact of LUC was included, the CF for marginal pork almost doubled in the 2015/16 and 2020/21 scenarios, making this the single largest contribution to the CF of marginal Australian pork. However, impacts were still lower than the 2010 baseline, declining by 25% in 2015/16 and 43% in 2020/21. These results suggest that productivity gains that have been achieved by the Australian pork industry could be partly offset by environmental impacts from feed production where land use change occurs. No studies have investigated the potential impact of LUC in marginal Australian grain production systems and further research is also needed in this area.

Optimisation of pork production

Improved herd performance contributed to the reduction in CF in comparison to the 2010 baseline. The herd performance of Australian pork production is still significantly lower than the herd performance of Demark and the Netherlands (Pork CRC, 2017), indicating that Australian pork production still has the potential for further gains in herd performance and consequentially reduction in environmental impacts. Nguyen et al (2012) found that combining improvement measures in three aspects: feed use, manure management, and manure utilisation, reduces the environmental costs by a factor of 1.4. Similarly, Groen et al. (2016) showed GHG emission mitigation options that improve HFC; decrease the amount of manure produced by pigs; improve crop yields; decrease the number of sows or piglets per growing pig needed and improve efficiency of N-fertiliser production had the highest reduction in environmental impacts.

Application of the research

The Pork CRC established an ambitious target in 2010 to reduce the CF of Australian pork to 1.0 kg CO_2-e kg LW^{-1}. In the following years, research to improve herd performance, and benchmarking performance, demonstrated substantial improvements in key indicators such as pigs weaned/sow/year and HFC. Noticeably, the best producers improved dramatically compared to industry average. In the 2010 industry benchmarking research (Wiedemann et al. 2016) a strong regression relationship was observed between HFC and CF for conventional piggeries, with low HFC resulting in low CF because of the positive interaction with waste stream VS, and because of reductions in the impact from upstream feed production.

In the present study, significant improvements were observed in herd performance compared to the industry average in 2010. When combined with changes in the proportion of different housing types and the increase in use of biogas, this resulted in 44% lower impacts for marginal pork production in 2015/16 and 63% for 2020/21 compared to 2010, excluding LUC. The most substantial contributor to reducing impacts was the change in manure management systems and specifically, the high proportion of biogas production and outdoor, deep-litter systems. Biogas production was found to be a common feature of the larger, new conventional piggery developments. The cost effectiveness of biogas installation is supported by the market for ACCUs, which provides a revenue stream from gas used to generate electricity, and excess flared gas. This has substantially improved the cost-effectiveness of biogas installation. However, cost effectiveness is still compromised at smaller scale piggery operations, limiting uptake at these piggeries. Uptake has also been limited in some states, such as WA, where electricity costs are lower than other parts of the country. This step change in environmental efficiency represents an industry advantage. However, because of the significant investment required to construct a new piggery and install biogas capture, and the difficult economic climate for producers at the time of writing this report, this industry transformation is expected to require a longer time horizon than suggested by the 2020/21 timeframe originally applied in this report.

Improvement scenarios: optimised biogas

The scenario analysis results indicated that 2020/21 optimised pork production (scenario 3) had lower CF compared to 2015/16 pork production (scenario 1), 2020/21 projected pork production (scenario 2) and the benchmark performance in 2010.

This scenario included the adoption of biogas at conventional piggeries at a rate of 90% of pigs produced, which was considered a practical industry maximum. Adoption rates for new or expanding piggery developments was slightly lower than this (84%), with all the proposed developments that did not include biogas being <10,000 SPU (<1000 sow farrow-finish). Currently, the cost-effectiveness of installing biogas diminishes with piggery size, and few small to medium piggeries have developed biogas capture for this reason. This suggests that, to achieve the 2020/21 optimised pork production outcome, the economic viability of biogas would need to change to enable adoption by small to medium conventional piggeries.

Several international studies have shown that the adoption of biogas can significantly reduce the CF of pork production. Lamnatou et al. (2016) showed that manure use for energy production by means of biogas generation can significantly reduce the CF and environmental impacts of pork production. Similarly, Cherubini et al., (2015) study indicated 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.

ERF and the uptake of biogas by the Australian pork industry

Currently, only 13.5% of Australian pork production is sourced from farm with biogas capture (Tait, 2018). While Skerman (2017) found that the ERF financial incentives have contributed to the current growing interest in on-farm biogas, the adoption of biogas by the industry has been quite slow. The McGahan et al (2013) biogas capture and energy generation feasibility studies found that the economic feasibility of biogas capture has depended on ERF (CFI) investment with about 30% of returns coming from this source. The implementation of biogas capture can require significant capital investment. Thus, credits generated through the ERF have heavily influenced the economic feasibility for the implementation of these biogas systems. These studies indicate that ongoing policy support for the carbon market is a key feature for the pork industry reducing emissions into the future.

Improvement scenarios: optimised diets

Imported soymeal is used in eastern Australia as an input to piggery diets, but inclusion rates vary depending on the least-cost alternatives. In WA, lupins are a common protein grain in pig rations and soymeal is not common, and in south eastern Australia other grains such as field peas, or co-products such as canola meal are commonly used. One strategy to reduce LUC emissions would be to increase alternative protein crops production for the north eastern Australian feed market, though this would need to be achieved without inducing an expansion of crop land and subsequent LUC emissions in Australia. This could reduce emissions from LUC associated with imported soymeal. Considering this contributed 0.95-1 kg CO_2-e kg LW^{-1} pork, this constitutes an important environmental priority. Similarly, 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).

Several international studies have investigated strategies to reduce the environmental burden associated with imported soybean. The most common strategy examined is reducing dietary CP in pig rations by increasing the inclusion rates of synthetic amino acids, reducing the proportion of high protein ingredients in feed. The optimised use of synthetic amino acid has been found to reduce the environmental impacts (Meul et al., 2012, Garcia-Launay et al., 2014, Ogino et al., 2013).

Improvement scenarios: increased turnoff weight

As an alternative scenario, the potential of marginal producers to increase production by increasing turnoff weight by 10 kg LW (to an average of 110 kg LW) from existing piggeries was also investigated (i.e. with housing and manure management equivalent to the 2015/16 scenario). This would result in approximately 10% more pork produced from these suppliers, and would result in turnoff weights that are closer to other major pork producers globally, such as the USA.

Impacts from pork produced using this scenario were equivalent to the 2020/21 scenario, with a CF of 1.3 kg CO_2-e kg LW^{-1}. Emissions from LUC were found to be lower (0.6 kg CO_2-

e kg LW^{-1}) because feed requirements were reduced. Similarly, Sonesson et al. (2014) showed that future scenarios to increase the meat produced from each pig would lead to fewer pigs needed to produce the same total meat volume, reducing sow and piglets needed. 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). This result provides an interesting, alternative view on how the industry could expand production with lowest environmental impacts, though it must be noted that for an increase of 10% in total pork output, the whole industry would need to adopt higher turnoff weights, and this would result in a different profile of housing and manure management than used in this study, where only marginal producers were considered.

Sensitivity Analysis

A series of sensitivity checks were performed to examine the impact of uncertain factors in the manure management model. In the marginal model, emissions from uncovered ponds and feed contributed less to CF than in previous benchmarking research because of the marginal systems used. Consequently, secondary emission sources required further examination to determine the effect of these on the model outputs. This was performed for the 2015 and 2021 scenarios to observe the change in sensitivity as the contribution of other gases changed.

Nitrous oxide emissions contributed 20-27% of emissions in 2015-2020. The emission factors used to determine emissions from soils when manure is applied, and from soils in free range areas, are based on European factors and have not been validated in Australia. Typically, soil research has shown lower nitrous oxide emission factors when Australian research has been conducted, and consequently a plausible scenario is that nitrous oxide emissions from manure application (EF = 0.01) and direct deposition in free range areas (EF = 0.02) are over estimated. A sensitivity check was done by applying the dryland fertiliser EF (0.003) and halving the free range EF, which resulted in a modest 3-5% reduction in GHG emissions in 2015 and 2020 respectively.

Impacts associated with manure substitution as a fertiliser were also examined by removing ammonia losses at the point of land application, and by increasing the utilisation rate of manure N from 0.5 to 0.8 for solids, and increasing the utilisation of P from 0.7 to 0.8 for both effluent and solids. Changing these factors altered total emissions by 2.4-4%.

Biogas yield was another factor that could vary between farms. IN the present study, biogas yield was 0.4 m^3 / kg VS with a methane content of 70%. To examine the sensitivity of this factor when excess electricity was being sold to the grid, the yield was increased to 0.55 m^3 / kg VS, which was about 90% of theoretical maximum. This resulted in a modest (1 or 2%) reduction in impacts via increased electricity production and export.

Clearly, imported soymeal is a sensitive input to the system and multiple factors influence the contribution of this product. We estimated that 0.24-0.25 kg soymeal was used per kg LW produced in the system, with LUC impacts of 3.3 kg CO_2-e kg soybean and 3.99 kg CO_2-e kg $soymeal^{-1}$. Impacts from LUC were found to vary depending on the source of soymeal in Latin America, with a range of 0.1-17.8 kg CO_2-e kg $soybean^{-1}$ (Castanheira and Freire, 2013) depending on whether soybeans were grown on land cleared from tropical rainforest or on land converted from degraded pasture. While this range was very large, mean results from this study were only slightly higher than the value used in the present study. Similarly, Leip et al. (2010) found that impacts from South American soymeal imported to Europe could range from 1.5 kg CO_2-e kg $soymeal^{-1}$ where only grassland was converted, to 10 kg CO_2-e kg $soymeal^{-1}$ where mostly forest was converted. The mean value reported was 3.1 kg CO_2-e kg $soymeal^{-1}$ for a mix of systems. This was slightly lower than the value used in the present study. Conversely, MacLeod et al. (2013) applied a value of 3.2 kg CO_2-e kg $soymeal^{-1}$ used in pig diets in their global study.

Using the average value from Leip et al. (2010) and MacLeod et al. (2013) into the present study resulted in a slight reduction in impacts from LUC (to between 0.75-0.8 kg CO_2-e kg

LW^{-1}). However, these studies did not apply cLCI methods, which would preferentially select for the soy production most likely to expand, which could include higher rates of deforestation. Applying a higher rate (i.e. 10 kg CO_2-e kg $soymeal^{-1}$, Leip et al. 2010) would result in impacts of 2.4-2.5 kg CO_2-e kg LW^{-1}. However, considering the marginal processes used in the current study were based on recently developed global consequential inventories (EcoInvent) it was considered a reasonable estimate of global soymeal production from expanding production.

Further sensitivity checking of background grain processes would be warranted to examine the impact of increasing marginal Australian cereal grain produced by intensification compared to expansion of crop land. However, data were not currently available to perform this analysis.

Conclusions

The Australian pig industry has experienced significant changes in the scale and level of productivity achieved by producers over the last four decades. In recent years, benchmarking performed by the Australian Pork CRC has shown a significant improvement in productivity, with more liveweight sold per sow, and lower HFC than previously reported. Over the same time period, new technology to capture biogas and generate electricity has been developed and implemented in a proportion of the industry. The present study determined the marginal Australian pork producers by surveying development approvals for new piggeries across the country. This survey revealed that a small but significant amount of expansion was proposed for the outdoor bred production sector, while conventional piggeries with biogas installations were the largest proportion of proposed expansion. A survey of these enterprises, most of which were current pig producers, revealed above average herd productivity levels. The high proportion of biogas installation compared to current averages indicated that future pork production is expected to be produced with a much lower CF than current industry averages suggest. This step change in environmental efficiency represents an industry advantage. However, because of the significant investment required to construct a new piggery and install biogas capture, and the difficult economic climate for producers at the time of writing this report, this industry transformation is expected to require a longer time horizon than suggested by the 2020/21 timeframe applied in this report. Other alternatives, such as increasing the weight of sale pigs or improving herd productivity levels were observed to also produce pork with low CFs, with potentially lower requirements for capital expenditure. However, market barriers for heavier carcases may also exist, limiting the capacity of the industry to pursue this approach.

The study found that feed impacts were of growing significance as a factor governing the future environmental impacts of pork production. Expanding production was found to increase demand for the global marginal protein meal (soymeal) with likely impacts on LUC emissions. Considering global warming is an international problem, such considerations should be taken into account by local industries.

Interestingly, the study revealed that marginal Australian pork production may be produced with a CF that was similar to the ‘average’ Australian chicken meat CF, indicating that previously identified differences between these meat types may be less significant than was thought to be the case. This provides the opportunity for the industry to position the product as a sustainable future diet choice.

Limitations

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. This extended beyond pork production to include markets for important grain inputs that are traded globally, such as soymeal. This means the results of cLCA modelling are scenario dependent and can never describe the full consequences of future production. However, the outcome of scenario modelling can reveal a general trend. In the present study, all scenarios revealed lower impacts than the baseline average and this trend is as significant, or more significant, than the specific impacts reported.

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 development will be needed to meet this demand, the lower prices may affect the scheduling of new developments. That is, developments are likely to be delayed until there are favourable market conditions. Thus, as the developments are likely be delayed, the current project findings would also be delayed.

Limitations also exist with respect to marginal background processes such as cereal grain production in Australia and global soymeal production. Further research is needed to determine if LUC emissions are also likely from expanding cereal or protein grain production in Australia. Likewise, further research would be beneficial to examine the impact of different global soymeal processes on Australian pork production, considering the sensitivity of this input.

Recommendations

Future pork production is expected to generate significantly lower environmental impacts than current industry averages, because of ongoing improvements in efficiency across the industry, but not without risks. This major outcome provides a number of opportunities for industry to further improve the CF of Australian pork and investigate sensitive or uncertain contribution sources that were previously less significant.

The present study investigated two potential future scenarios and an alternative increased live weight scenario, with all showing much lower impacts than average production, suggesting the industry is well positioned as a sustainable choice for the future. There are a range of research related recommendations and broader industry communications and policy recommendations coming out of this work.

Communications and Policy

Firstly, considering the global need for increased meat production and the dynamics of the Australian industry, it is recommended that the industry move environmental communications to focus on marginal production systems. The results from the limited number of scenarios in the present study showed the CF of increased pork production to be low relative to baseline figures for the pork industry and other meat products. These results are more relevant for retailers, policy makers and consumers where the information is being used to make decisions (i.e. choosing pork or another protein source) because it is the marginal supply that is affected rather than the 'average'. Thus, the results from the present study are more suitable for all applications that implicitly or explicitly are likely to result in a change in demand. However, four limitations should be acknowledged with respect to the current report: i) only a small number of scenarios were modelled, ii) only carbon footprint was modelled, but impacts associated with energy, water, land and nutrient losses are also highly relevant, iii) the study focused on production only, but would be more relevant to consumers if it extended to a 'table ready' product, and iv) the results have not been published in the scientific literature. Expanding the study to address these limitations in the scope of the current work would be beneficial for communications to the general public or government.

A key support mechanism that has resulted in uptake of biogas production was the Australian Government CFI (later changed to the current ERF) legislation. The returns from sale of ACCUs has diminished under the ERF, and while proposed uptake of biogas is high, this could reduce if policy (and market) support for the ACCU market diminished. Current low returns from sale of ACCUs has already made participation for new operations considerably less attractive. This policy platform is an important aspect of promoting a low emission future for the industry.

Promotion of opportunities for industry to sell electricity to the grid would also substantially improve the economics of some biogas developments, and this has been hampered by the electricity market to date and therefore may be an area where policy changes are required to improve market access.

Research and Development – Mitigating impacts

Reduced future CFs for Australian pork in the present study were primarily driven by better herd productivity, increased biogas uptake and efficiency, and improved feed efficiency. Ongoing research to support these goals, and demonstrate rates of improvement, are valuable in supporting the industry's low environmental impact. With respect to biogas adoption, specific areas of research, development or extension are required to improve the cost effectiveness and uptake of biogas among smaller (<1000 sow farrow-finish) producers. Industry restructuring to utilise excess electricity or develop offtake agreements for the sale of electricity would also improve the economics of biogas.

Alternatively, upgrading biogas to natural gas could result in cost effective strategies for increasing revenue from excess biogas production, and industry projects are already underway to address some of these goals. In the future, optimisation of biogas yield to improve the amount of energy produced would also provide an important avenue for increasing co-product output in the form of electricity or gas.

Beyond biogas, opportunities may also exist to improve spent litter management to reduce GHG. Reducing the frequency and duration of spent litter stockpiling, and avoiding composting, would result in lower GHG emissions from spent litter and could result in more nitrogen available in the cropping system. Additionally, replacing synthetic fertiliser nitrogen with effluent, sludge and spent litter results in a small offset in GHG emissions, which could be enhanced by reducing nitrogen losses from manure management systems. This could provide additional, modest reductions in GHG. Uncertainties also remain in the estimation of emissions from manure management (for example, emissions from soil in free range and manure application areas) and it is possible that these are smaller sources than currently estimated. Further research could confirm that the CF from these systems is therefore lower than currently estimated.

Feed efficiency, and particularly protein feed efficiency, has been identified as a major area of impact from the current study, particularly as the impact from manure management and energy use diminishes. This suggests that in the future, environmental improvement will largely come through 'low environmental impact' diet formulation. Nutrition and environmental research and development have tended to operate in separate spheres traditionally, but scope exists to integrate these and deliver new benefits for the industry. Specifically, reduction of demand for protein grains and meals is an important environmental goal. Global protein meal production is an expanding sector and has been targeted because of the known impacts caused by this sector in regions such as South America. Reducing the requirement for protein grain, and specifically soymeal, is therefore a growing environmental priority. This could be progressed via diet optimisation (with synthetic amino acids for example) and / or via inclusion of other protein grains into diets and promotion of better, locally grown protein grains in sustainable grain farming systems. Secondly, optimisation of HFC is a key ongoing priority for reducing future environmental impacts. Another area of focus regarding feed is around the potential for on-site feed production out of food waste (via insects or processing techniques). This would reduce grain demand and could be achieved by utilising excess heat and electricity produced from biogas.

Research and Development – Improving the knowledge base

The present study investigated two future scenarios and one alternative production scenario for future Australian pork. However, many more scenarios could be constructed, and some additional areas of investigation are warranted. For example, production with higher weaning percentages and higher growth rates would be expected to further reduce impacts. Additionally, modified diets (as noted above) could be tested using cLCA to determine the potential for decreasing impacts.

There are also risks for the future impact of pork that require further investigation. In the present study, cereal grain production was modelled assuming the expansion in supply would arise from intensification (higher nitrogen inputs) rather than expansion of the area of land used for cereal grain production and associated land use change carbon losses. While the inventory of soil carbon in Australia's crop land currently indicates minimal carbon losses, further research is required to understand if grain production can expand sustainably without soil carbon losses.

For the industry to reduce carbon emissions beyond the levels indicated in the current report, it is likely that offset mechanisms such as soil carbon or vegetation carbon sequestration would be required. Investigating the market opportunities from offsetting carbon emissions on piggery sites could be one area of further investigation for the industry.

References

ABARES (2017) *Agricultural commodity statistics 2017: Rural commodities- meat general*. Canberra, Australian Bureau of Agricultural and Resource Economics. Available at: http://www.agriculture.gov.au/abares/publications/display?url=http://143.188.17.20/anrdl/DAFFService/display.php%3Ffid%3Dpb_agcstd9abcc0022017_IugZg.xml

ABS (2015) *Fertiliser Use, Australia, year ended 30 June 2015*. Australia, Australian Bureau of Statistics. Available at: http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/4627.0Main%20Features72014-15?opendocument&tabname=Summary&prodno=4627.0&issue=2014-15&num=&view=

AgriFutures (2009) *Lupin production in Australia Introduction - Publications & Resources*. Australia, AgriFutures. Available at: https://agrifutures.infoservices.com.au/downloads/10-124

AgriFutures (2017a) *Field pea*. Australia, AgriFutures. Available at: http://www.agrifutures.com.au/farm-diversity/field-pea/

AgriFutures (2017b) *Lupin*. Australia, AgriFutures. Available at: http://www.agrifutures.com.au/farm-diversity/lupin/

AgriFutures (2017c) *Grain Sorghum*. Australia, AgriFutures. Available at: http://www.agrifutures.com.au/farm-diversity/grain-sorghum/

APL (2012). *Australian Pig Annual 2011-2012*. Australia, Australian Pork Limited (APL). Available at: http://australianpork.com.au/wp-content/uploads/2013/09/Australian-Pig-Annual-2011-12-LR.pdf

Aranda, G. and Cleary, G. (Eds.) (2002*) PigStats 2000 and 2001. Australian Pig Industry Handbook*. Kingston, A.C.T., Pig Research and Development Corporation ; St. Leonards, N.S.W., Australian Pork Corporation.

Australian Government (2016) *Australian Energy Statistics, Publications and Data Downloads*. Australia, Office of the Chief Economist. Available at: https://www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Australian-energy-statistics.aspx

Australian Government Productivity Commission (2005) *Australian Pigmeat Industry Productivity Commission Inquiry Report. 2005*. Australia, Australian Government. Available at: http://www.pc.gov.au/inquiries/completed/pigmeat-2005/report/pigmeat.pdf

Basset-Mens, C., Van der Werf, H.M.G., (2005) *Scenario-based environmental assessment of farming systems: the case of pig production in France*. Agric. Ecosyst. Environ. 105, 127–144.

Barona, E., Ramankutty, N., Hyman, G. and Coomes, O.T. (2010) *The role of pasture and soybean in deforestation of the Brazilian Amazon*. Environmental Research Letters, 5(2), p.024002.

Baumgartner, D.U., de Baan, L., Nemecek, T. (2008) *European Grain Legumes e Environment-friendly Animal Feed? Life Cycle Assessment of Pork, Chicken, Meat, Egg, and Milk Production. Grain Legumes Integrated Project (GLIP)*. Agroscope Reckenholz-T€anikon Research Station ART, Zürich.

Boerema, A., Peeters, A., Swolfs, S., Vandevenne, F., Jacobs, S., Staes, J. and Meire, P., (2016) *Soybean trade: balancing environmental and socio-economic impacts of an intercontinental market*. PloS one, 11(5), p.e0155222.

Castanheira, É. G., & Freire, F. (2013) *Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems*. Journal of Cleaner Production, 54, 49-60.

Cederberg C. (1998) *Life Cycle Assessment of Milk Production — A comparison of Conventional and Organic Farming. SIK Report 643*. ISBN 91-7290-189-6

Cederberg C, and Stadig M (2003) *System expansion and allocation in Life Cycle Assessment of milk and beef production*. Int J LCA 8, 350–356

Cherubini, E., Zanghelini, G.M., Alvarenga, R.A.F., Franco, D. and Soares, S.R. (2015) *Life cycle assessment of swine production in Brazil: a comparison of four manure management systems*. Journal of Cleaner Production, 87, pp.68-77.

Chobtang, J., McLaren, S.J., Ledgard, S.F. and Donaghy, D.J. (2017) *Consequential Life Cycle Assessment of Pasture-based Milk Production: A Case Study in the Waikato Region, New Zealand*. Journal of Industrial Ecology, 21(5), pp.1139-1152.

Commonwealth of Australia (2016) *National Inventory Report (NIR) 2014 (revised): Volume 1. Australian National Greenhouse Accounts*, Australia: Australian Government, Department of the Environment and Energy (DEE).

Dalgaard, Randi. *The environmental impact of pork production from a life cycle perspective. (2007)* Diss. Videnbasen for Aalborg Universitet VBN, Aalborg Universitet Aalborg University, Det Teknisk-Naturvidenskabelige Fakultet. The Faculty of Engineering and Science, Institut for Planlægning Department of Development and Planning.

Dalgaard, R., Halberg, N., and Hermansen, J. E. (2007) *Danish pork production – An environmental assessment,* DJF Animal Science, 82, 34 pp.

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M. and Pengue, W.A., (2008) *LCA of soybean meal*. The International Journal of Life Cycle Assessment, 13(3), p.240-254.

de Vries, M., de Boer, I.J.M. (2010) *Comparing environmental impacts for livestock products: a review of life cycle assessments*. Livest. Sci. 128, 1e11.http://dx.doi.org/10.1016/j.livsci.2009.11.007.

Dourmad, J.Y., Ryschawy, J., Trousson, T., Bonneau, M., Gonz_alez, J., Houwers, H.W.J., Hviid, M., Zimmer, C., Nguyen, T.L.T., Morgensen, L. (2014) *Evaluating environmental impacts of contrasting pig farming systems with life cycle assessment*. Animal 8, no. 12 (2014): 2027-2037

Eriksson, I.S., Elmquist, H., Stern, S., Nybrant, T. (2005) *Environmental systems analysis of pig production — the impact of feed choice* (12 pp). The International Journal of Life Cycle Assessment 10, 143–154.

Fehlenberg, V., Baumann, M., Gasparri, N.I., Piquer-Rodriguez, M., Gavier-Pizarro, G. and Kuemmerle, T. (2017) *The role of soybean production as an underlying driver of deforestation in the South American Chaco*. Global environmental change, 45, pp.24-34.

Fertilizer Australia (2018) *Australian Fertilizer Market 2012-2016*. Australia, Fertilizer Australia. Available at: https://www.fertilizer.org.au/Fertilizer-Industry/Australian-Fertilizer-Market

FGP (2016) *Australian feed grain supply and demand report 2016*. Australia, Australian, Feed Grain Partnership (FGP). Available at: http://www.sfmca.com.au/items/1093/FGP%20Report%20October%202016.pdf

Garcia-Launay, F., van derWerf, H.M.G., Nguyen, T.T.H., Le Tutour, L., Dourmad, J.Y. (2014) *Evaluation of the environmental implications of the incorporation of feed-use amino acids in pig production using Life Cycle Assessment*. Livestock Science 161, 158–175.

GRDC (2017) *Grownotes TM Field Pea*. Australia, Grains Research and Development Corporation (GRDC). Available at: https://grdc.com.au/__data/assets/pdf_file/0027/292923/GRDC-GrowNotes-Field-Pea-Southern.pdf

González-García, S., Belo, S., Dias, A.C., Rodrigues, J.V., da Costa, R.R., Ferreira, A., de Andrade, L.P. and Arroja, L. (2015) *Life cycle assessment of pigmeat production: Portuguese case study and proposal of improvement options*. Journal of Cleaner Production, 100, pp.126-139.

Groen, E.A., van Zanten, H.H.E., Heijungs, R., Bokkers, E.A.M., de Boer, I.J.M. (2016) *Sensitivity analysis of greenhouse gas emissions from a pork production chain*. J. Clean. Prod. 129, 202e211.

Harrison, M.T., Cullen, B.R., Tomkins, N.W., McSweeney, C., Cohn, P. and Eckard, R.J., 2016. The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems. Animal Production Science, 56(3), pp.370-384.

Halberg, N., Hermansen, J., Kristensen, I.S., Eriksen, J., Tvedegaard, N. (2007) *Comparative environmental assessment of three systems for organic production in Denmark*. In: Proceedings Organic Agriculture in Asia 2008, pp. 249e261.

Hirschfeld, J., Weiss, J., Preidl, M., Korbun, T. (2008) *Klimawirkungen der Landwirtschaft in Deutschland (Climate impacts of German agriculture)*. Schriftenreihe des IOW 186/08. IOW, Berlin.

ISO (2006a) *Environmental management—Life cycle assessment: Principles and framework*. ISO14040, Geneva. International Standard Organisation (ISO).

ISO (2006b) *Environmental management—Life cycle assessment: Requirements and Guidelines*. ISO14044, Geneva. International Standard Organisation (ISO).

Lamnatou, C., Ezcurra-Ciaurriz, X., Chemisana, D. and Plà-Aragonés, L.M. (2016) *Environmental assessment of a pork-production system in North-East of Spain focusing on life-cycle swine nutrition*. Journal of Cleaner Production, 137, pp.105-115.

LEAP (2014) *Environmental performance of animal feed supply chains: guidelines for quantification: draft for public review*. Rome, Food and Agricultural Organisation of the United Nations - Livestock Environmental Assessment and Performance Partnership. (FAO UN - LEAP)

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F.,Grandgirard, D., Monni, S., Biala, K., 2010. Evaluation of the Livestock Sector's Contribution to the EU Greenhouse Gas Emissions (GGELS) e Final Report. European Commission, Joint Research Center, Ispra.

MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Vellinga, T., Henderson, B. & Steinfeld, H. 2013. Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome.

McGahan, E. Valentine, J., Heubect, S., and Murphy, C. (2013) *Five piggeries biogas capture and energy generation feasibility studies 4C-102-Final-Report-130420*. Australia, Pork CRC. Available at: http://porkcrc.com.au/wp-content/uploads/2013/08/4C-102-Final-Report-130420.pdf

Meul, M., Ginneberge, C., Van Middelaar, C. E., de Boer, I. J. M., Fremaut, D., and Haesaert, G.: (2012) *Carbon footprint of five pig diets using three land use change accounting methods*, Livest. Sci., 149, 215–223.

Mushalik, M. (2017) *Almost Half of Australia's Petrol, Diesel and Jet Fuel Imports come from South Korea and Japan Crude Oil Peak*. Available at: http://www.resilience.org/stories/2017-08-21/almost-half-australias-petrol-diesel-jet-fuel-imports-come-south-korea-japan/

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L. (2011) *Environmental Assessment of Danish Pork - Internal Report*. Denmark, Faculty of Agricultural Science, Aarhus University. Available at: http://web.agrsci.dk/djfpublikation/djfpdf/ir_103_54761_indhold_internet.pdf

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L. (2012) *Environmental costs of meat production: the case of typical EU pork production*. J. Clean. Prod. 28, 168–176.

NSW DPI (2018) *National Grains Life Cycle Assessment project*. Australia, New South Wales Department of Primary Industries (NSW DPI). Available at: https://www.dpi.nsw.gov.au/climate-and-emergencies/research/grains-lca

Noya, I., Villanueva-Rey, P., González-García, S., Fernandez, M.D., Rodriguez, M.R. and Moreira, M.T. (2017) *Life Cycle Assessment of pig production: A case study in Galicia*. Journal of Cleaner Production, 142, pp.4327-4338.

OEC (2018) *Where does Australia import Soybean Meal from?* The Observatory of Economic Complexity (OEC). Available at: https://atlas.media.mit.edu/en/visualize/tree_map/hs92/import/aus/show/2304/2016/

Ogino, A., Osada, T., Takada, R., Takagi, T., Tsujimoto, S., Tonoue, T., Matsui, D., Katsumata, M., Yamashita, T., Tanaka, Y. (2013) *Life cycle assessment of Japanese pig farming using low-protein diet supplemented with amino acids*. Soil Sci. Plant Nutr. 59, 107–118.

Pork CRC (2017) *Pork CRC Initiatives March 2017*. Australia, Pork CRC. Available at: http://porkcrc.com.au/wp-content/uploads/2017/02/Pork-CRC-Initiatives-March-2017-Circulation.pdf

Pré-Consultants (2018) *SimaPro 8.5 Software,* Amersfoort, Netherlands: Pré-Consultants.

Pulse Australia (2015) *Australian Lupin Exports*. Australia, Pulse Australia. Available at: www.pulseaus.com.au/storage/app/media/industry/AU-lupin-exports.pdf

Pulse Australia (2018) Field pea. Australia, Pulse Australia. Available at: http://www.pulseaus.com.au/growing-pulses/bmp/field-pea

Queensland Alliance for Agriculture and Food Innovation (2018) *Sorghum Crop Outlook March 2018 (Australia)*. Australia, Queensland Alliance for Agriculture and Food Innovation (QAAFI). Available at: https://qaafi.uq.edu.au/article/2016/11/sorghum-crop-outlook-march-2018-australia

Queensland Government (2012) *Overview of the sorghum industry*. Australia, Queensland Government. Available at: https://www.daf.qld.gov.au/business-priorities/plants/field-crops-and-pastures/broadacre-field-crops/sorghum/overview

Ransley., R. and Cleary, G. (Eds.) (1994) *PigStats93. Australian Pig Industry Handbook*. Kingston, A.C.T., Pig Research and Development Corporation ; St. Leonards, N.S.W., Australian Pork Corporation.

Reckmann, K., Traulsen, I., Krieter, J. (2012) *Environmental impact assessment e methodology with special emphasis on European pork production*. Review. J. Environ. Manag. 107, 102e109.

Reckmann, K., Traulsen, I., Krieter, J. (2013) *Life cycle assessment of pork production: a data inventory for the case of Germany*. Livest. Sci. 157, 586–596.

Reckmann, K., Blank, R., Traulsen, I. and Krieter, J. (2016) *Comparative life cycle assessment (LCA) of pork using different protein sources in pig feed*. Archiv fuer Tierzucht, 59(1), p.27.

Reinhard J, Weidema B P, Schmidt J H (2010) *Identifying the marginal supply of wood pulp*. 2.-0 LCA consultants, Aalborg, Denmark. Available at: https://lca-net.com/publications/show/identifying-marginal-supply-wood-pulp/

Reinhard, J., and Rainer Zah. (2009) *Global environmental consequences of increased biodiesel consumption in Switzerland: consequential life cycle assessment*. Journal of Cleaner Production 17, S46-S56.

Rotz, C. (2004) *Management to reduce nitrogen losses in animal production*, Journal of animal science, 82(13_suppl), pp. E119-E137.

Samuel-Fitwi, B., Nagel, F., Meyer, S., Schroeder, J. P., & Schulz, C. (2013). *Comparative life cycle assessment (LCA) of raising rainbow trout (Oncorhynchus mykiss) in different production systems*. Aquacultural Engineering 54, 85-92.

Schmidt, Jannick Højrup (2007) *Life cycle assessment of rapeseed oil and palm oil*. Ph. D. thesis, Part 3: Life cycle inventory of rapeseed oil." (2007).

Schmidt, J.H., Merciai, S., Thrane, M., Dalgaard, R. (2011) *Inventory of Country Specific Electricity in LCA e Consequential and Attributional Scenarios. Methodology report v2*. Aalborg, Denmark: Available at: https://lca-net.com/files/Inventory_of_country_specific_electricity_in_LCA_Methodology_report_20110909.pdf

Schmidt, Jannick H., and Bo P. Weidema (2008) *Shift in the marginal supply of vegetable oil*. The International Journal of Life Cycle Assessment 13.3, 235.

Skerman, A.G. (2017) *Practical options for cleaning biogas prior to on-farm use at piggeries*. Ph.D. thesis, Australia, University of Queensland. Available at: https://espace.library.uq.edu.au/data/UQ_466035/s43057494_M_Phil_Thesis_Rev.pdf?Expires=1527664029&Signature=Sp8NFcarubyC3fGg6TlT7Kdu9WNbxODf7ro9~abqgc0byz~1YHN924JGjLsU6bSAS37WZY~~PDW7KWqoevkMZGGJJ8nwRh61HJuo1iza2asiBMhkjSult8e--35LQ6qHEYvfqsNWnwfYhd0u27WMQgqDbDD-v~hWwJLALpjoVzjLAGHJgRojSvQOMbmo1i2F9Zoff8oJHP~XNyKBx5aO7NoP7lDpoU4t~26jIp4kzOFr3UlqPLkp82Z6h9vJkuCniNlaKgd7MkwlOiEYuA9g3ZO7iQeMe8Z3YkYiC5kY-yRedfj3oTeLQfSb-sX4vUg-SvjMWJJGhsGHEG7AgUEuWw__&Key-Pair-Id=APKAJKNBJ4MJBJNC6NLQ

Skerman, A., Wilis, S., Mcgahan, E. and Marquardt, B. (2015) *PigBal 4. A Model for Estimating Piggery Waste Production*, Toowoomba, Australia: Department of Agriculture, Fisheries and Forestry (DAFF).

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. and Miller, H. (2007) *Climate change 2007 - the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*. Cambridge University Press.

Sonesson, U., Lorentzon, K., Andersson, A., Barr, U.K., Bertilsson, J., Brunius, C., Emanuelsson, M., Borch, E., Göransson, L., Gunnarsson, S. and Hamberg, L. (2014) Paths to a sustainable food sector guided by LCA-exemplified by pork production. American Center for Life Cycle Assessment, Vashon, USA, pp.1255-1264.

Tait (2018) *BIOENERGY SUPPORT PROGRAM – TRANSITION (RESEARCH). 4C-115*. Australia, Pork CRC. Available at: http://porkcrc.com.au/wp-content/uploads/2018/01/4C-115-Final-Research-Report_final-1.pdf

Thomassen, M. A., Dalgaard, R., Heijungs, R., and de Boer, I. (2008) *Attributional and consequential LCA of milk production*. The International Journal of Life Cycle Assessment 13.4, 339-349.

Thrane, M. (2006) *LCA of Danish Fish Products. New methods and insights*. Int J Life Cycle Assessment (2006) 11: 66. doi:10.1065/lca2006.01.232

Tonini, D., Hamelin, L., Wenzel, H and Astrup, T. (2012) *Bioenergy Production from Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including Land Use Changes*. Environmental Science & Technology 46 (24), 13521-13530.

van der Werf, H. M. G., Petit, J., and Sanders, J. (2005) *The environmental impacts of the production of concentrated feed: the case of pig feed in Bretagne*, Agr. Syst., 83, 153-177.

van Zanten, H.H., Bikker, P., Meerburg, B.G. and de Boer, I. (2018) *Attributional versus consequential life cycle assessment and feed optimization: alternative protein sources in pig diets*. The International Journal of Life Cycle Assessment, 23(1), pp.1-11.

Van Zanten, H.H.E., Bikker, P., Mollenhorst, H., Meerburg, B.G., de Boer, I.J.M. (2015) *Environmental impact of replacing soybean meal with rapeseed meal in diets of finishing pigs*. Animal 9 (11), 1866e1874. http://dx.doi.org/10.1017/S1751731115001469

Vázquez-Rowe, I., Rege, S., Marvuglia, A., Thénie, J., Haurie, A., and Benetto, E. (2013) Application *of three independent consequential LCA approaches to the agricultural sector in Luxembourg.* The International Journal of Life Cycle Assessment 18.8, 1593-1604.

WA Department of Primary Industries and Regional Development (2017) *Western Australian lupin industry.* Australia, WA Department of Primary Industries and Regional Development (WA DPIRD). Available at: https://www.agric.wa.gov.au/grains-research-development/western-australian-lupin-industry

Weidema BP, Frees N, Nielsen A (1999) *Marginal production technologies for life cycle inventories.* Int J Life Cycle Assess 4(1):48–56

Weidema, B.P. (2003) *Market information in life cycle assessment. Copenhagen: Danish Environmental Protection Agency. (Environmental project 863).* Available at: http://www.miljoestyrelsen.dk/udgiv/Publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf

Wiedemann, S.G. and McGahan, E.J. (2011) *Environmental impacts of alternative waste treatment systems for Australian piggeries using LCA.* Australia, Australian Pork Limited (APL). APL Project No. 2009/1011.336.

Wiedemann, S. G., Eugene J. McGahan, and Caoilinn M. Murphy. (2016) *Environmental impacts and resource use from Australian pork production assessed using life-cycle assessment. 1. Greenhouse gas emissions.* Animal Production Science 56.9, 1418-1431.

Wiedemann, S, McGahan, E & Murphy, C (2012) *Energy, Water and Greenhouse Gas Emissions in Australian Pork Supply Chains: A Life Cycle Assessment.* Australia, Pork Co-operative Research Centre (CRC).

Wiedemann, SG, McGahan, EJ, Grist, S & Grant, T (2010) *Environmental assessment of two pork supply chains using life cycle assessment*, Project No PRJ-003176 & PRJ-004519, RIRDC Publication No 09/176. Barton, ACT, Rural Industries Research and Development Corporation (RIRDC).

Wiedemann, SG & McGahan, EJ (2011) *Environmental assessment of an egg production supply chain using life cycle assessment, Final Project Report*, AECL Publication No 1FS091A, December 2011, Australian Egg Corporation Limited, North Sydney, NSW.

Wiedemann, S., Davis, R., McGahan, E., Murphy, C. and Redding, M. (2017a) *Resource Use and Greenhouse Gas Emissions from Grain-Finishing Beef Cattle in Seven Australian Feedlots: A Life Cycle Assessment*, Animal Production Science, 57(6), pp. 1149-1162.

Wiedemann, S., McGahan, E. and Murphy, C. (2017b) Resource Use and Environmental Impacts from Australian Chicken Meat Production, Journal of Cleaner Production, 140, pp. 675-684.

Williams, A.G., Audsley, E., Sandars, D.L. (2006) *Determining the Environmental Burdens and Resource use in the Production of Agricultural and Horticultural Commodities. Main Report, Defra Research Project IS0205.* Cranfield University and Defra, Bedford.

Appendix 1

Identification of marginal feed cereals and proteins marginal suppliers

Table 9. Marginal suppliers of major feed cereals and proteins

Product	Marginal supplier	Determining product	Co-products	References
Wheat	Australia (also Canada and EU countries)	Wheat – for human or animal production	Straw or no co-product (straw considered a residual)	NSW DPI (2018)
Sorghum	Australia, QLD	Sorghum- for animal use	n.a	AgriFutures (2017c) Queensland Alliance for Agriculture and Food Innovation (2018) Queensland Government (2012)
Field pea	Australia, SA, VIC	Field pea - for animal use	n.a	AgriFutures (2017a) GRDC (2017) Pulse Australia (2018)
Lupins	Australia, WA	Lupins- for animal use	n.a	AgriFutures (2017b) Pulse Australia (2015) WA Department of Primary Industries and Regional Development (2017) AgriFutures (2009)
Soy bean	The global market's largest suppliers are Brazil and Argentina	Soybean- for animal use	Soy oil	Boerema et al (2016) (OEC, 2018)

Inputs associated with transport and feed milling were considered to be the same as the national average reported by Wiedemann et al. (2016) and repeated here in Table 10.

Table 10. Transport and feed-milling inventory data

Inventory data replicated from Wiedemann et al. (2016).

Input	Type	Unit	Mean
One-way transport distance used for livestock and purchased inputs	Distance staff travel to farm	km	22
	Distance straw from supplier to farm	km	85
	Distance from feed mill to farm	km	85
Feed-milling energy inputs per tonne of ration delivered to the pig farm	Electricity	(kWh/t)	32
	Diesel	(L/t)	4.2
	Gas	(MJ/t)	67
	Transport of commodities to feed mill	(km)	85

Appendix 2

Identification of marginal energy suppliers

As the transmission and trade of grid electricity is limited by location, marginal source of electricity production varies between countries or regions. Table 11 shows the Australian electricity generation percent share and average annual growth of major fuel types, however there are large differences between State energy mixes (Table 12). The marginal electricity supply for each State was identified using the method suggested by Schmidt et al. (2011). The business-as-usual approach in Schmidt et al. (2011) method assumed the increase in the proportions of different electricity production sources to be similar to the recent past increases. Thus, the marginal electricity supply for Australia was based on the 10-year average annual growth differences in the proportion of sources for electricity production between 2005 and 2015 as reported by Australian Government (2016), as well as state specific data. The resultant State marginal electricity grid mix is shown in Table 13. The geographic market for fossil fuels is global, with almost half of Australia's petrol, diesel and jet fuel coming from imports (Mushalik, 2017), thus the marginal supply of fossil fuels was modelled as given in the consequential database of EcoInvent V3.

Table 11. Australian electricity generation by fuel type; percent share and average annual growth (Australian Government, 2016)

	2009-10		2014–15		Average annual growth		
	GWh	Share (%)	GWh	Share (%)	2009-10 (%)	2014–15 (%)	10 years (%)
Fossil fuels	**219,360**	**91**	**217,871**	**86.3**	**-**	**3.1**	**0.4**
Black coal	124,478	52	107,639	42.7	-3.7	1.8	-2.1
Brown coal	55,968	23	50,970	20.2	-0.9	10.6	-0.8
Gas	36,223	15	52,463	20.8	1.0	-3.6	9.7
Oil	2,691	1	6,799	2.7	-11.6	35.6	9.3
Renewables	**19,711**	**8**	**34,488**	**13.7**	**-**	**-6.9**	**5.3**
Hydro	12522	5	13,445	5.3	13.3	-27.0	-1.9
Wind	4798	2	11,467	4.5	26.0	11.8	23.5
Bioenergy	2113	1	3,608	1.4	-9.1	11.4	-1.0
Solar PV	278	0.1	5,968	2.4	78.2	22.9	59.3
Geothermal	0	0	1	0	0	27.3	2.7

Table 12. State electricity generation by percent share and 5-year growth (Australian Government, 2016)

	NSW			VIC			QLD			WA			SA		
	2010-11	2014-15	% dif	2010-11	2014-15	% dif	2010-11	2014-15	% dif	2010-11	2014-15	% dif	2010-11	2014-15	% dif
Non-renewable fuels															
Black coal	83.49%	81.73%	-1.76%	0.00%	0.00%	0.00%	71.45%	65.29%	-6.17%	32.41%	28.02%	-4.39%	0.00%	0.00%	0.00%
Brown coal	0.00%	0.00%	0.00%	91.83%	85.49%	-6.34%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	29.31%	20.15%	-9.16%
Natural gas	6.52%	7.04%	0.52%	2.32%	3.88%	1.56%	22.74%	26.74%	4.00%	56.72%	53.65%	-3.07%	46.36%	38.29%	-8.07%
Oil products	0.08%	0.44%	0.36%	0.07%	0.22%	0.15%	0.58%	1.75%	1.17%	4.43%	11.25%	6.82%	0.62%	1.51%	0.89%
Other **a**	0.37%	0.00%	-0.37%	0.21%	0.00%	-0.21%	1.62%	0.00%	-1.62%	3.22%	0.00%	-3.22%	1.85%	0.00%	-1.85%
Total non-renewable	**90.46%**	**89.21%**	-1.25%	**94.43%**	**89.59%**	-4.84%	**96.39%**	**93.78%**	-2.61%	**96.78%**	**92.92%**	-3.86%	**78.14%**	**59.95%**	-18.19%
Renewable fuels															
Bagasse, wood **b**	0.35%	0.86%	0.51%	0.00%	0.03%	0.03%	1.28%	2.27%	0.99%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Biogas **b**	0.49%	0.73%	0.24%	0.61%	1.19%	0.58%	0.15%	0.13%	-0.02%	0.35%	0.34%	-0.01%	0.54%	0.65%	0.11%
Wind	0.73%	2.14%	1.41%	2.58%	5.43%	2.85%	0.04%	0.05%	0.01%	2.25%	4.38%	2.12%	20.02%	32.84%	12.82%
Hydro	7.24%	4.84%	-2.40%	2.01%	2.07%	0.06%	1.50%	0.95%	-0.55%	0.00%	0.55%	0.55%	0.03%	0.08%	0.05%
Solar PV	0.72%	2.21%	1.49%	0.37%	1.69%	1.32%	0.62%	2.81%	2.19%	0.62%	1.82%	1.20%	1.27%	6.47%	5.20%
Geothermal	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total renewable	**9.54%**	**10.79%**	1.25%	**5.57%**	**10.41%**	4.84%	**3.61%**	**6.22%**	2.61%	0.00%	0.00%	0.00%	**21.86%**	**40.05%**	18.19%

Table 13. State marginal electricity supply mix applied in the present study

Technology (in %)	NSW	VIC	QLD	WA	SA
Non-renewable fuels					
Coal	-	-	-	-	-
Oil	-	-	-	64%	-
Natural Gas	-	35%	90%	-	-
Renewable fuels					
Solar	51%	15%	10%	10%	16%
Hydro	-	-	-	-	-
Geothermal	-	-	-	-	-
Wind	49%	49%	-	25%	84%

Appendix 3

Manure emissions were determined using the emission factors outlined in the Australian NIR (Commonwealth of Australia 2016), with the key factors shown in Table 14. These factors are not expected to change over time were considered appropriate for determining future emissions.

Table 14. Piggery greenhouse-gas emission factors applied in the study

Emission source	Emission and units	Factor
Maximum methane potential	Ultimate methane yield (Bo)	0.45
Manure – emissions from uncovered anaerobic pond	MCF	0.75 (NSW)
		0.77 (QLD)
		0.74 (VIC)
		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	N2O-N [a]	0
Manure – emissions from outdoor (dry lot)	N2O-N [a]	0.02
Manure – emissions from deep litter	N2O-N [a]	0.01
Manure – emissions from uncovered anaerobic pond	NH3-N [a]	0.55
Manure – emissions from outdoor (dry lot)	NH3-N [a]	0.3
Manure – emissions from deep litter	NH3-N [a]	0.125
Manure – emissions from stockpile	MCF	0.02 (NSW)
	MCF	0.02 (WA)
	N2O-N [b]	0.005
	NH3-N [b]	0.2
Indirect N2O from volatilised NH3	N2O-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

Combined heat and power (CHP) modelling assumptions

Piggeries with covered ponds or digesters and CHP units were modelled based on expected performance from a correctly designed and maintained CHP unit, using assumptions provided in Table 15, reported previously by Wiedemann et al. (2012).

Table 15. Assumptions for farm scale combined heat and power (CHP)

Parameter	Value and Range
Electrical energy conversion efficiency	35% (32-38%)
Thermal energy conversion efficiency	40%
Parasitic heat demand	0%
Parasitic electrical demand (stirring)	20%