PATHWAYS TO CARBON NEUTRAL PORK PRODUCTION

MITIGATION STRATEGIES AND THEIR APPLICATION TO A VICTORIAN PIGGERY CASE STUDY

Report prepared for the Co-operative Research Centre for an Internationally Competitive Pork Industry

By

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Executive Summary

Greenhouse gas emissions are an important environmental concern for Australia and the world. The Australian Government has established targets to unconditionally reduce emissions 5% from 2000 emission levels by 2020 (DCCEE 2011). This is a target that all industries must contribute to if it is to be achieved. As part of the pork industries' commitment to reducing GHG, the Pork CRC has set the target that 60% of pork production will have reduced GHG emissions to approximately 1 kg CO_2-e/kg pork by June 2019.

To date, there has been no comprehensive investigation of what could be done on farms to achieve the Pork CRC target. This project aimed to map out a pathway for the industry to substantially reduce GHG emissions from conventional pork production towards the rate of '1 kilogram of CO_2-e/kg pork'.

This study reviewed a range of options that could be used to reduce emissions from pork production. These options were discussed with a farmer advisory group and a rating system was used to identify options with the best potential for reducing emissions.

A carbon footprint case study was conducted for a Victorian conventional farrow-finish piggery as part of the study, and mitigations were applied. The carbon footprint of the piggery, with a wheat based diet and no covered ponds, was 4.86 kg CO_2-e/kg LW.

Mitigations were modelled using a combination of strategies as follows:

1) CAP-CHP with standard production
2) CAP-CHP with optimised effluent storage and utilisation
3) CAP-CHP with optimised diet (low GHG feed ingredients)
4) CAP-CHP with optimised diet, optimised effluent storage and utilisation, soil carbon sequestration and tree planting.

We found that emissions could be reduced by 59% by installing CAP-CHP units to all the piggery sites. The farm has begun to implement this, with the first covered pond already in place and others to follow. The final emissions from the four scenarios ranged from 0.6-2 kg CO_2-e/kg LW. Reductions to meet the pork CRC target (1 kg CO_2-e/kg pork) required application of several approaches together. The qualitative cost-benefit analysis suggests that covering ponds may be cost effective for a reasonable proportion of the industry. Changes to effluent management may also be cost effective, though these may have fairly long payback times. Other options such as modification of ration components or reduction of dietary CP, are likely to increase costs making this less attractive.

This study did not cover every possible mitigation option, but selectively covered those thought to be most applicable by the farmer advisory group. Further investigation of mitigation strategies will be beneficial as the industry pursues targeted reductions in GHG.

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List of Abbreviations

ADG	Average daily gain
CAP	Covered anaerobic pond
CF	Carbon footprint
CFI	Carbon Farming Initiative
CHP	Combined heat and power
DCCEE	Department of Climate Change and Energy Efficiency
FCR	Feed conversion ratio
FU	Functional unit
GHG	Greenhouse gas
HRT	Hydraulic retention time
HSCW	Hot standard carcase weight
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LPG	Liquid petroleum gas
LW	Live weight
MCF	Methane conversion factor

Introduction

Greenhouse gas emissions are an important environmental concern for Australia and the world. The Australian Government has established targets to unconditionally reduce emissions to a 5% reduction on 2000 emission levels by 2020 (DCCEE 2011). The Australian pork industry has been investigating greenhouse gas emissions from the production system using the life cycle assessment (LCA) tool for several years, with the first analysis completed in 2010 (Wiedemann et al. 2010). This study showed that the full 'life cycle' GHG emissions from two different pork supply chains ranged from 3.1-5.5 kg/kg HSCW, depending on the nature of the housing system in which pigs were kept. Wiedemann et al. (2012) showed that emissions may be reduced considerably by installing biogas plants to generate electricity and minimise methane emissions from the anaerobic treatment of effluent in open ponds. However, there are few piggeries where such technology is currently installed.

As a commitment to reducing emissions in the industry, the Australian pork CRC has set a target to reduce greenhouse gas emissions from Australian piggeries to 1 kg CO_2-e/kg LW pork. Based on current emission levels from conventional piggeries (used here to mean piggeries with liquid effluent treatment systems), this is a considerable reduction. However, there are several options available to the industry that will help in achieving this. This project aims to map out a pathway for the industry to substantially reduce GHG emissions from conventional pork production towards the target emission rate of '1 kilogram of CO_2-e/kg LW pork'. The project covers the whole 'life cycle' of the pork production system using life cycle assessment (LCA). The project aims not only to conduct an analysis of emissions and emission reduction potential, but to show the steps that a pig farmer could follow to achieve this.

Research objectives

There were two main objectives for this project:

1. To develop, using a participatory learning case study approach, a pathway for pork producers towards reaching the CRC target of 1 kg CO_2-e/kg LW.
2. To characterise a broad range of GHG mitigation options using a life cycle approach for the case study piggery, and investigate their technical potential for uptake in the pork industry.

Life cycle assessment in agricultural systems

LCA is a well established research method defined by international standards (ISO 2006a, b). LCA can be used to investigate GHG emissions over the entire life cycle of a product or service. Studies are conducted in four stages; i) goal and scope establishment, ii) data collection (life cycle inventory - LCI), iii) life cycle impact assessment (LCIA) and iv) interpretation (see Figure 1). The degree of flexibility within the research framework and the specific data collection processes employed allow a considerable degree of variance between studies. Consequently, LCA results are not commonly comparable without careful review of critical methodological elements and standardisation of results. These elements primarily relate to the goal and scope of the study and the data collection (inventory) approach used.

Agricultural systems have some unique properties that require careful treatment within LCA. In particular, the long production cycle and open system complicate collection of production data and environmental impact data. Hence, studies (including this one) are often based on modelling rather than measurement of impacts.

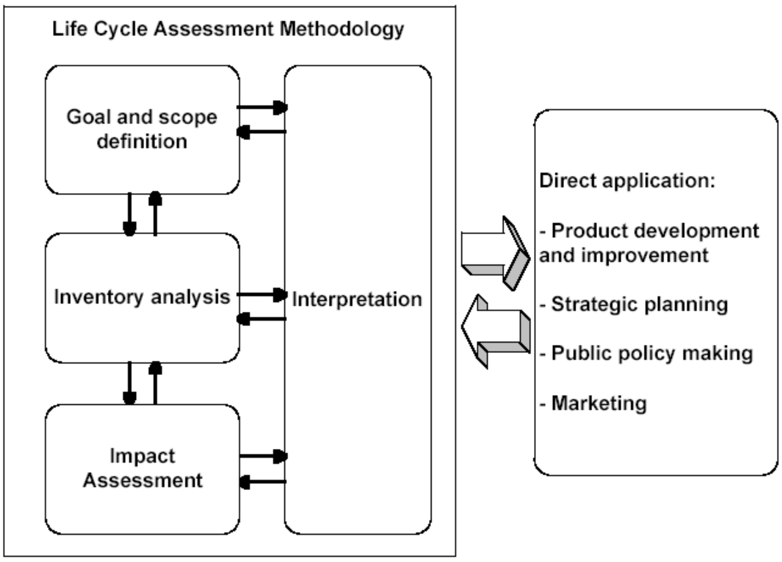

Figure 1 – General Framework for LCA and its Application (ISO 2006a: 14040)

Drivers for reducing the carbon footprint of a piggery

As part of this project, discussions were held with the case study farmer and other industry members to identify drivers for reducing emissions from piggeries. The main drivers for reducing the carbon footprint, based on these discussions, were:

- Economics – via reducing energy and resource use, and via sales of carbon credits.
- Improving on-site energy reliability via on-site generation.
- Potential marketing advantages for 'environmentally friendly' pork.
- More efficient management of resources and nutrients.

Economics is expected to be the biggest driver for reducing GHG emissions. The reason for this is two-fold. Firstly, the existence of government financial incentives such as the Carbon Farming Initiative (CFI) are economically attractive. Murphy et al. (2012) found that the financial return from this and other associated energy schemes could provide 50% of the total return associated with a covered anaerobic pond with a combined heat and power (CAP-CHP) system. Secondly, rising costs of energy and unreliable electricity supply can be overcome with being self-sufficient in energy, reducing farm input costs.

There are a number of recent studies assessing the feasibility of installing CAP systems, with or without energy recovery, for Australian piggeries. McGahan et al. (2012) carried out a series of feasibility studies for five small to medium conventional piggeries throughout Australia. Each of the case studies looked at different energy recovery options with effluent being treated in a CAP. These studies found that the most favourable payback periods ranged from 1.8-8.5 years. Similar paybacks were found for three piggeries investigated by FSA Consulting (2012a, b, c). This highlights the economic viability of installing energy recovery systems at piggeries; and with the ever increasing prices of energy, the feasibility will continue to improve.

Many piggeries are located in regions of Australia that do not have access to a reliable source of power. The issues with power include momentary short outages and voltage surges or reductions (Meta Economics Consulting Group 2013). These issues can cause farmers to install their own generators onsite, which use large quantities of diesel at high costs. Therefore, the existence of a reliable, low cost source of energy onsite, in the form of biogas, is an attractive alternative to conventional fossil fuel energy.

Another possible driver is the unexplored opportunity for marketing pork as "low GHG" or "carbon neutral", as consumers may find this attractive.

Some of the mitigation options available to producers have added benefits in addition to reducing the level of GHGs being released to the atmosphere. For example, by improving the utilisation of nutrients from the effluent stream as a fertiliser for crop production. Currently, piggery manure treatment systems generate relatively high losses of nitrogen to the atmosphere as ammonia. Some alternative effluent treatment systems, such as covered ponds, may greatly reduce these losses making larger amounts of nutrient available for utilisation. Provided this can be used to replace synthetic fertiliser, there will be further reductions to GHG and energy demand, via the avoided production of synthetic fertiliser. This depends on full utilisation of these nutrients to ensure they do not lead to environmental harm via other nutrient loss pathways.

GHG mitigation options for conventional piggeries

A conventional piggery has sheds in which the flooring is usually partly or fully slatted, or includes open channel dunging areas. The effluent, which includes faeces, urine, water, and spilt feed, accumulates in underground drainage channels or pits. These are then regularly flushed or emptied to remove the effluent from the sheds. Conventional production was chosen as the basis of this study as opposed to deep litter or outdoor production, because it represents the majority of the industry. In a survey of production systems conducted by Australian Pork Ltd (APL 2010), it was found that 83% of Australian pork producers used anaerobic ponds to treat piggery effluent.

The aim of this project was to determine a series of mitigation options that could be practically implemented, provided there was sufficient incentive, now or in the mid-term future (5-10 years). These mitigation options were then modelled for a case study piggery. The studies by Wiedemann et al. (2012) and Wiedemann et al. (2010) showed that GHG emissions from conventional Australian pork production are dominated by methane production in anaerobic ponds (62-64% of total emissions). After manure management, the biggest contributor to GHG (18-40% of total emissions) was feed production. The GHG emissions associated with energy use and services contributed between 8-12%.

It is possible to reduce GHG emissions from pig production in three broad ways; i) through the direct or indirect reduction of GHG from the production system, ii) by reducing inputs that have embedded GHG emissions generated from manufacture and production, and iii) by offsetting emissions. Offsetting emissions can be achieved by either; a) sequestering carbon in soil or vegetation on site, or b) generating new products from the piggery system, such as electricity or nitrogen fertiliser which offset the use of fossil fuels (and therefore GHG emissions) elsewhere in the economy. Figure 2 shows the range of mitigation options reviewed.

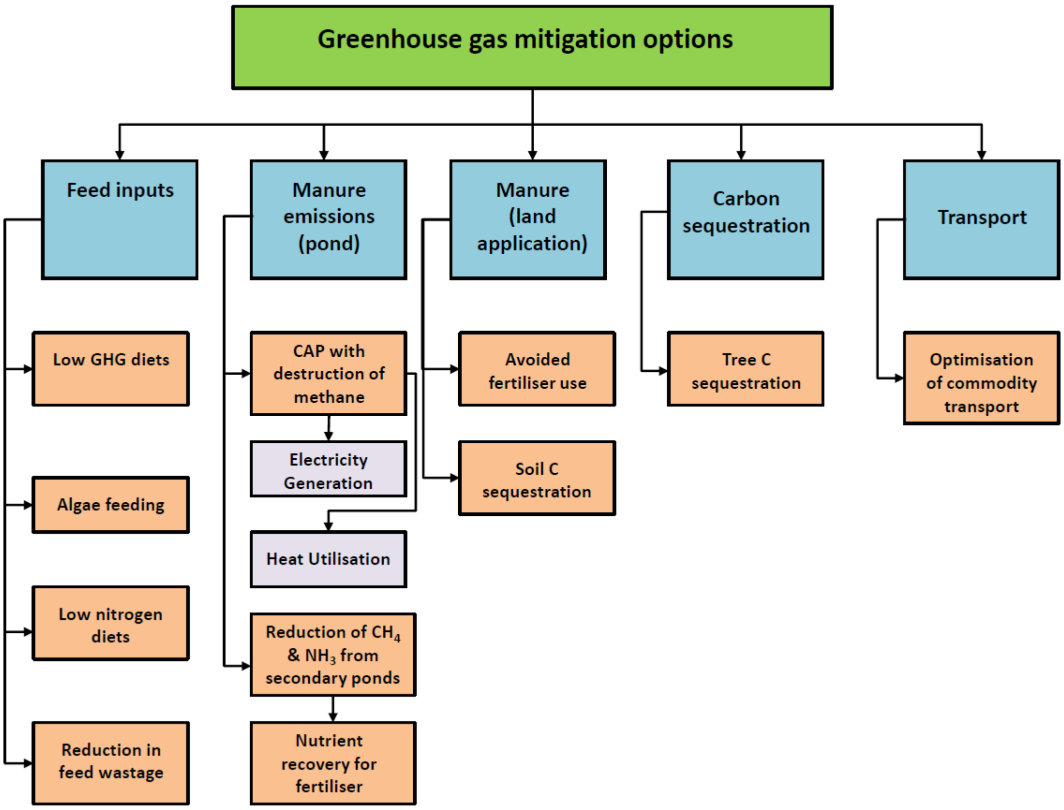

Figure 2 - GHG mitigation options for piggeries

The following sections outline a series of opportunities for mitigating emissions at a conventional piggery.

Feed inputs

Low GHG diets

All standard feed inputs require energy during their production, resulting in GHG emissions, and may also directly generate nitrous oxide during production. These emissions associated with feed production contribute significantly to the total carbon footprint of pork. Lowering the GHG emissions associated with pig diets can be achieved by replacing high GHG intensity feed inputs with lower GHG intensity alternatives.

We distinguish here between four categories of feed products, based on the production system they are sourced from, to differentiate the level of associated environmental burdens. The four categories are; primary products, co-products, by-products, and waste products.

Primary products are single products produced for the purpose of feed production. Examples are wheat, barley and sorghum. **Co-products** are generated from another production system as a secondary product, but are high value products in their own right. Examples include canola meal, meat meal and tallow. Both primary products and co-products are attributed a proportion of the 'environmental burden' of the production system where they arose.

Some valuable feed sources are low value **by-products** from other production systems. Examples include whey and some yeast products. Where the value is negligible and demand is low, it is reasonable to assume that no environmental burden is associated with these products. **Waste products** are those that are rejected from the human food supply system because of oversupply and diverted to animals. Products such as waste bread, milk and fruit are examples of products that can be readily fed to pigs.

Replacing High GHG Intensity Ingredients with Lower Intensity Alternatives

Some feed ingredients have a higher GHG intensity than others. For example, a high proportion of soymeal in Australia is imported from the USA and Brazil. Because of the transport distance, and more importantly the contribution of GHG from direct Land Use Change (dLUC) for Brazilian soymeal, this feed source has high levels of GHG intensity. If this component of the diet could be replaced with Australian protein meals, with no dLUC emissions, emissions will be lower. However, this is also likely to come at a higher cost which must be taken into account.

Replacing Regular Ingredients with By-Products or Waste Products

By-product feeding may reduce the emissions from pig diets. Recovering by-products from the human food manufacturing industry can also allow piggery owners to save money, as often by-products represent a less expensive source of nutrients than traditional feeds. We assume that a by-product that has negligible value carries no 'environmental burden' from the production system it arose from. Where transport is paid by the piggery to bring the product to the site, the impacts of transport are attributed to pork production.

Another option is to feed waste products from the human supply chain. Where these products have negligible value they are attributed no environmental burden. Where these products are diverted from land fill, they may offer an offset equivalent to the emissions that would have otherwise arisen from disposal via land fill. For example, Themelis & Ulloa (2007) report conservative values of methane yields of approximately 0.05 m^3/kg of municipal solid waste (MSW) landfilled for MSW with an estimated biomass content of 69.5%. Scharff & Jacobs (2006) report higher methane yields for household waste in landfills, at 0.1 m^3/kg. Where readily digestible feed products are placed in land fill, the emission potential would be much higher. For example, Bouallagui et al. (2003) found methane production from biodigested fruit and vegetable waste (FVW) was equivalent to 0.45 m^3 CH_4/kg VS. Gunaseelan (2004) found that the ultimate methane yield for fruit waste ranged between 0.18 and 0.73 m^3 CH_4/kg VS.

Under current laws, swill (food that has been offered for human consumption) and waste meat products are not allowed to be fed to pigs. This ensures the highest standards of food safety are achieved. However, it also results in the wastage of some high value products that could otherwise be fed to pigs. In the case of waste meat products, there may be opportunities to heat treat or render these products to make them suitable for feeding to pigs, reducing environmental impacts. This would require thorough investigation if it is deemed to be a possible option.

New Feed Alternatives: Algae

Feeding pigs alternative nutrient sources such as algae introduces the possibility of reducing GHG emissions associated with feed production. The most suitable cultivation systems for algae derived feeds and fuel are called “high-rate ponds”, which are shallow, raceway type systems, with a low degree of mixing (Brune et al. 2009). In Australia, MBD Energy Limited use CO_2 emissions from coal-fired power plants combined with sunlight and waste water to produce algae which can then be used as livestock feed (Grainger & Beauchemin 2011).

Some of the advantages that algae feeds have over conventional livestock feeds are by using land unsuitable for food crops, reuse and recovery of waste nutrients, use of brackish or saline waters, and sequestration of CO_2 from power plants. A recent study commissioned by the Pork CRC (Henman 2012) determined that the inclusion of algal meal as a replacement for canola meal did not cause any significant reduction of pig performance if correctly formulated into the diet.

However, despite the many positive reviews of algae as an alternative low GHG feed, preliminary analysis by Grant & Batten (2013) shows that the net GHG reduction was equivalent to just 0.02 kg CO_2-eq/kg HSCW or approximately 0.01 kg CO_2-eq/kg LW, after parasitic energy demands were taken into account. These authors suggest that if algae could be produced on piggery effluent ponds, the best use for the algae would be as an energy feedstock, which could lead to an offset of 1.75 kg CO_2-eq/kg HSCW.

Low nitrogen diets

Ball & Mohn (2003) reviewed the literature on potential feeding strategies to reduce GHG emissions from pigs. They identified that low CP diets with amino acid supplementation was an effective strategy for reducing GHG emissions. The reduction of crude protein in feed leads to a decrease in the amount of nitrogen (N) excreted. This then leads to a decrease in the nitrous oxide and ammonia emissions from the piggery. Piggery diets are formulated with least-cost formulation methods, with some variance in actual dietary CP. In practice, protein levels are often higher in rations than is actually required (Aarnink & Verstegen 2007). Lowering dietary CP will usually result in higher costs for added synthetic amino acids.

Cromwell (1996) stated that a 2% percentage point reduction in dietary protein, with the addition of lysine, could reduce N excretion by 15-20%. Osada et al. (2011) compared a typical control diet (171 g CP/kg) against a low protein (145 g CP/kg) diet supplemented with amino acids. This low protein diet resulted in a 28.7% decrease in N excretion, while manure emissions were reduced by 39.1%. Moehn & Susenbeth (1995) determined that a 20% reduction in dietary N reduced N excreted by 35%. Atakora et al. (2003) found that changing from a high protein diet (19.3%) to a low protein diet (16%) resulted in 20% lower N excretion rates. It is clear that low protein diets can have a profound effect on N excretion. Madrid et al. (2013) determined that reducing the CP by 6% with amino acid supplementation reduced ammonia emissions by 19.9% with no effects on growth, performance and carcass characteristics.

Some studies have found that feeding a low CP diet supplemented with amino acids can have a detrimental effect on growth rates and productivity (Guay et al. 2006, Opapeju et al. 2008). Otto et al. (2003) found that despite including amino acids in reduced protein diets, if the CP was reduced by more than 3 percentage units of the total diet, the amount of N retained by the pigs decreased. This led to reductions in ADG and feed conversion efficiency. Osada et al. (2011) found that there was no negative effect on the pigs in their study when dietary CP was reduced by 2.5 percentage points in the diet.

For low protein diets to be an effective mitigation strategy, both the reduction in manure emissions and feed production, and the additional emissions from manufacturing synthetic amino acids, must be accounted for.

Reduction in feed wastage

Feed is one of the major costs for piggeries. Therefore, minimisation of feed wastage is beneficial to the industry as it reduces expenditure. However, minimisation of feed wastage is difficult to achieve in practice because of the feeding habits of pigs. Any feed that is wasted will either drop on the slats/flooring and be flushed to the effluent treatment system with the manure or will remain in the litter of deep litter sheds. McGahan et al. (2010) showed that a 5% variation from the standard 10% allowance for feed wastage can result in ± 30% variations in the effluent volatile solids (VS) for an average sized grower pig (25 – 40 kg LW). Because VS loading is the primary determinant of methane generation from effluent treatment, a reduction in feed wastage will lead to lower GHG. However, it should be noted, that if a piggery has the capacity to cover its ponds, then the importance of feed wastage on GHG emissions is diminished, as the methane is captured. None-the-less, lower feed wastage improves the overall system efficiency, reduces costs and reduces embedded emissions in feed production, milling and transport.

Pond emissions

CAP with destruction of methane

The use of CAPs to capture and destroy or utilise biogas is especially interesting for pig producers, as it is now a recognised abatement methodology under the Carbon Farming Initiative (CFI). This methodology allows for the generation of additional revenue for piggery owners through the sale of carbon credits.

Covered anaerobic ponds are designed in much the same way as uncovered anaerobic ponds, however a high quality geo-membrane cover is used to capture the methane gas that is produced. Pre-treatment (solids separation) of the effluent stream is optional, but is recommended when diets contain high proportions of husky type grains such as barley. These ponds are designed with a hydraulic retention time (HRT) of 40-50 days, which is less than uncovered anaerobic ponds, and a variable sludge accumulation period between 6 months and several years.

Table 1 shows the methane production from two recent covered pond studies in Australia and New Zealand. Few other studies were found in the literature, and these were considered the most relevant to Australian conditions and designs.

Table 1 – Methane generation rates from CAPs

System Characteristics	Methane Production (m^3 CH_4/kg VS)	Reference
Covered pond – screened piggery effluent (New Zealand)	0.279	Craggs et al. (2008)
Covered pond – screened piggery effluent (Australia)	0.48	Birchall (2009)
DCCEE comparison value for uncovered ponds		
DCCEE – B_o of 0.45, MCF of 90%	0.405	DCCEE (2010)

It is not clear if the very high yields measured by Birchall (2009) were representative of the system investigated or if there were confounding factors, such as methane arising from residual VS that was in the pond prior to the trial.

Methane from a CAP can be destroyed via flaring. The default combustion efficiency of an open flare is 98% (DCCEE 2012).

CAP with destruction of methane and electricity generation

The methane gas captured in the CAP can be combusted in a generator to produce electricity. The power generation units which are suitable for use in the Australian piggery industry are spark-type gas engines and micro-turbines (Murphy et al. 2012). Methane can be converted to electricity onsite using these engines, which can be assumed to operate with efficiencies of 25-35%.

CAP with destruction of methane and heat utilisation

Another energy recovery option available to piggeries is burning the methane in a boiler to produce heat and hot water for the piggery. A typical boiler can be assumed to have an efficiency of 90%. The heat produced can be used to offset the annual gas usage of the site leading to reductions in the energy expenditure of the piggery. Because of the large volumes of gas, heat generation may be well beyond the requirements of the piggery.

CAP with destruction of methane and combined heat and power

Combined heat and power (CHP) generation is another energy recovery option. A variety of reciprocating engines can be used, including spark ignition and compression ignition engines. Methane is burnt in a reciprocating gas engine to drive an alternator to produce electrical energy. Simultaneously the heat energy exhausted by the engine is recovered, usually in the form of hot water (80 – 90°C). The conversion of methane gas into electrical energy is approximately 25-35%; while an additional 45-55% can be recovered as heat energy.

Reduction of methane and ammonia emissions from secondary ponds

Most piggeries that have covered anaerobic pond systems have a secondary pond system which allows the effluent to be treated further and acts as extra storage capacity in times of wet weather. Secondary ponds are typically anaerobic and may produce significant amounts of methane and ammonia. There is the option to mitigate these emissions by ensuring that the hydraulic retention time of these ponds is kept to a minimum. The system is termed short HRT and involves irrigation of the effluent from the secondary ponds. Effluent contains nutrients that are beneficial for crop or pasture production and some salts; therefore it is beneficial as a fertiliser offset. The short HRT system significantly reduces emissions associated with secondary ponds. Table 2 shows the emission factors used for these systems.

Table 2 – Emission factors used for a short HRT secondary pond system

Parameter	Value	Reference	Uncertainty (SD or range)
B_o	0.45	DCCEE (2010)	-
MCF	0.135	IPCC (2006)	0.03 - 0.3
Direct N_2O	0.002	IPCC (2006)	0.002-0.004
Volatilised as NH_3	0.25	IPCC (2006)	0.15-0.30
Indirect N_2O	0.01	DCCEE (2010)	-

Land application

Fertiliser offset

The production of fertilisers requires significant amounts of energy and subsequent GHG emissions. Urea is the most commonly used fertiliser in Australia. In the 2009-10 Agricultural Resource Management Survey, 33% of all agricultural businesses reported using urea (ABS 2011). Animal manure in the form of effluent or sludge can be used to replace fertiliser for crop production, thereby reducing, or avoiding, the required mass of urea and other fertilisers. Urea is a particularly GHG and energy intensive product. Table 3 gives a typical range of GHG and energy use values for 1 kg of nitrogen in urea using both Ecoinvent and using AustLCI unit processes.

Table 3 – GHG and energy use per kg N in Urea

Impacts	Unit	Value – used in Australian research	Range
GHG	kg CO_2-e	1.9	1.9 - 7.1
Fossil energy	MJ LHV	54.4	54.4 - 126.4

Where effluent and/or sludge utilisation results in avoided fertiliser use, it is reasonable to apply an offset to the pork production system equivalent to the avoided fertiliser use. This is done using a process known as system expansion in LCA, taking into account the relative efficiency of nutrient utilisation from the two different sources.

Wiedemann et al. (2010) suggested that nutrients present in sludge and effluent cannot be considered directly transferable on a mass basis with synthetic fertiliser. The main reason for this is that nutrients contained in effluent and sludge may be in a form that is less available for plant uptake. Additionally, 20-30% of nitrogen in sludge or effluent is typically lost during application (Rotz 2004) unless the sludge or effluent is rapidly incorporated or irrigated into the soil. The loss rate from fertiliser N is likely to be lower than this, particularly if it is banded in the soil. Nutrient substitution ratios depend on management. Improved management of effluent or solids application, and improved management of the soil/crop system may result in higher efficiencies of nutrient utilisation. The report by Wiedemann & McGahan (2011) revised the values presented by Wiedemann et al. (2010) to reflect "best management". Firstly, it was assumed that best practice application of sludge or effluent would include incorporation (either via ploughing or irrigation) within 6 hours of application, reducing N losses to zero and increasing the amount of N available for plant use. Secondly it was assumed that through soil testing and careful soil management, phosphorus and potassium utilisation could be increased by 10% from the rate suggested previously in Wiedemann et al. (2010).

Soil carbon sequestration

Few studies have been published that quantify soil carbon change under pastures irrigated with effluent or with manure application in Australia. Currently, the possible contribution to the net carbon footprint of pork is unknown. Across the world, soil carbon levels have often been found to increase under pastures when improved species and fertiliser are added (Conant et al. 2001). However, soil carbon sequestration under improved pastures (phosphorus fertiliser and introduced legumes) compared with native pastures in Australia has been shown to vary from zero (Wilson et al. 2010) to between 0.26 and 0.72t C/ha/yr (Chan et al. 2010).

The study by Lal (2004) described how the application of manure and/or effluent to a nutrient depleted soil can increase the soil carbon content. This study determined that if best management practices (BMP) such as the application of manure and compost and adoption of conservation tillage with cover crops are put in place, then measured rates of C sequestration can range between 0.05 and 1.0 t C/ha/yr. Mugiwra (1976), cited by Conant et al. (2001) determined that dairy effluent application resulted in increasing soil C content. Hountin et al. (1997) assessed the soil carbon levels following the application of piggery effluent and various tillage conditions for maize production. It was found that an increase in application rate had a linear effect on the total carbon stored in the soil. This study determined that the long-term application of piggery effluent to soil lead to increased concentration of C in the soil profile. Rochette & Angers (2000) reviewed the soil carbon effects of 19 years of piggery effluent application to agricultural soils. The application of piggery effluent was found to increase soil carbon from 0.1 to 0.37 t C/t soil.

The wide variation in SOC levels under pastures and cropland is due to the many factors that influence storage levels, e.g. soil type, climate, fertiliser strategies and management. The significant variability in reported carbon sequestration rates in Australia means the soil carbon sequestration rates must be viewed with caution.

Carbon sequestration

Tree carbon sequestration

Farm tree plantings are a recognised carbon sequestration method under the CFI. However, there is a distinct lack of information available on the carbon sequestration rates for different tree species in different parts of Australia (Grace & Basso 2012).

Paul et al. (2008) looked at seven eucalypt plantations in southern NSW and central Victoria with relatively low rainfall (500-800 mm/yr). The rate of carbon sequestration ranged between 4.17 and 4.86 t C/ha/yr for the higher productivity eucalypt species. Fensham & Guymer (2009) provide values for above ground biomass carbon stores in the major ecosystem types in Queensland by mean annual rainfall zones. These range from 20 t C/ha for acacia open woodland in a semi-arid climate to 500 t C/ha for eucalypt tall open forest in a humid climate. This study states that it would take approximately 70 years for forest carbon levels to reach those of uncleared vegetation. This would lead to carbon accumulation rates ranging between 1 and 26 t CO_2-e/ha/yr over 70 years.

Grace & Basso (2012) conducted a study to determine the area of land required to offset 1000 t CO_2-e in the south-eastern region of Queensland using three tree species with both high and low productivities. Carbon sequestration rates were simulated over a 30 year time period. They were found to range from 1.6-10.5 t C/ha/yr for Eucalyptus, 0.2-9.0 t C/ha/yr for hoop pine, and 1.9-9.8 t C/ha/yr for Pinus. The total area required to offset the 1000 t CO_2-e ranged from 1-45 ha for the different tree species. Tree planting is likely to be a minor source of sequestration for pig farms because of the limited availability of land, but was still considered in the assessment.

Transport

Optimisation of commodity transport

Major transport stages for piggery supply chains include grain and feed input commodities (to the feed mill), transport of prepared ration from the feed mill to the piggeries, transport of pigs between piggeries (at multiple site facilities) and transport of finished pigs to the meat processing plant. Staff transport to and from work is also relevant. Wiedemann et al. (2012) determined that contributions from transport contributed around 5-10% of total energy use. The contribution to GHG is much lower but should still be considered for completeness.

Methodology

This project aimed to map out a pathway for the industry to substantially reduce GHG emissions from conventional pork production towards the target emission rate of '1 kilogram of CO_2-e / kg LW pork'. The study was restricted to the primary production segment of the supply chain, through to production of live weight at the farm gate. The study investigated GHG emissions only, using global warming potentials (GWP) of 25 and 298 for methane and nitrous oxide respectively, after the IPCC (Solomon et al. 2007). Modelling was done using SimaPro™ 7.3.

Description of the case study piggery

The piggery is a conventional medium-sized farrow-to-finish operation located in Victoria. It is located in a Mediterranean climatic region, with annual average rainfall of 369 mm/yr. Pigs are housed in conventional sheds with effluent collection channels underneath the pens. Figure 3 shows the movement of the pigs between the different units at the piggery. The farm consists of breeder, weaner, grower and grower-finisher units located on several sites.

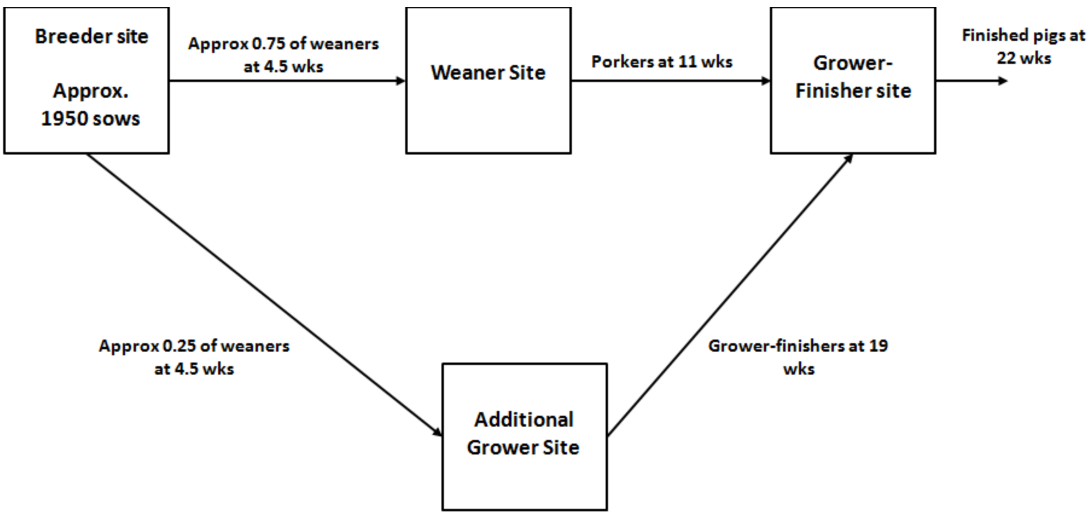

Figure 3 – Pig movements between the different units

A covered anaerobic pond (CAP) has recently been installed at one of the grower-finisher sites on the farm. This CAP also takes manure from one of the weaner sites. At present the methane produced is flared. However, the piggery plans on combusting the methane to generate electricity and heat energy using a combined heat and power (CHP) unit. There are also plans to build a CAP at the breeder unit and at the additional grower unit.

In order to establish the baseline scenario for this study, it was assumed that there were no CAPs installed (all effluent treated in open anaerobic ponds). The baseline scenario involves treatment in a primary anaerobic pond with a hydraulic retention time (HRT)>100d, and further treatment in secondary and tertiary ponds.

Inventory data

Detailed production data, livestock inventories and input data were collected for a 12-month period from the case study farm from producer records and from a visit to the piggery. A 12-month data collection period was considered sufficient to account for seasonal variation in grain supply and energy use associated with heating and cooling.

Table 4 – Herd Production Data

Production Data	
Pigs weaned / Sow / yr	24.7
FCR* (whole herd)	3.86
Carcase dressing percentage	78%

* Feed conversion ratio

The major purchased inputs to the piggery, in terms of the carbon footprint, were feed and energy. Services, such as transport, were included in the analysis (data not shown).

The diet used for this analysis was based on a typical Victorian predominantly wheat and barley. Table 5 shows the aggregated, simplified standard Victorian rations for the breeder, weaner, and grower/finisher units at the piggery.

Table 5 – Aggregated, simplified standard Victorian rations for farm

Commodities	**Breeder ration (kg/t)**	**Weaner ration (kg/t)**	**Grower-Finisher ration (kg/t)**
Barley	589.6	0.0	229.7
Wheat	273.8	775.1	575.9
Plant protein meals	48.4	116.3	120.0
Animal protein by-products	70.2	93.8	69.4
Dairy by-products	5.7	0.0	0.0
Oil	6.5	10.6	0.6
Low cost additives	5.2	2.5	3.2
High cost additives	0.5	1.8	1.1
Total (kg)	**1000.0**	**1000.0**	**1000.0**

Energy use data primarily consisted of electricity and gas use (liquid petroleum gas (LPG), natural gas). Relatively small volumes of diesel and petrol were also used. Transport data were collected for all transfers of materials within the supply chain. Major transport stages included grain and feed input commodities to the feed mill; transport of prepared ration from the feed mill to the piggeries; transport of pigs between piggeries (at multiple site facilities) and transport of finished pigs to the meat processing plant. Transport data were calculated as tonne kilometres and were classified according to truck type, using AustLCI transport unit processes. Staff transport to and from work for all facilities was calculated from staff records and reported travel distances. Table 6 shows the annual energy inputs used at the piggery.

Table 6 – Annual Energy Inputs

Energy	Units	Breeder Site	Weaner Site	Grower/ Finisher Site	Additional Grower site	Total
On-farm						
Electricity	kWh	758 192	63 086	225 470	42 857	1 089 605
Diesel	L	0	0	39 300*	0	39 300
Petrol	L	0	0	5 200*	0	5 200
Gas (LPG, butane)	L	0	40 310	22 050	0	62 360
Feedmill						
Electricity	kWh	0	0	225 470	0	225 470
Transport						
Feedmill to farm	tkm	49 634 579	1 720 046	0	9 544 230	60 898 855
Farm to abattoir	tkm	0	0	7 425 000	0	7 425 000
Staff travel	km	64 000	6 400	115 200	1 920	187 520

*These values represent overheads for the whole farm

Emissions modelling

Emissions were modelled from the inventory of purchased inputs using background inventory processes in the AustLCI database. Emissions associated with feed use were modelled using the feed grains inventory data reported in Wiedemann e tal. (2010) and Wiedemann & McGahan (2011). Manure excretion was modelled in PigBal (Casey et al. 2000) from recorded diet properties and pig production to predict excreted N and VS. We applied emission factors that best represented the conditions experienced by the piggery, based on Wiedemann et al. (2012). These are summarised in Table 7.

Table 7 – Best science emission factors for conventional effluent treatment systems

Parameter	Best Science		Uncertainty (SD or range)
	Value	Reference	
Ultimate methane yield (B_o)	0.45	IPCC (1997)	0.38-0.52
Methane conversion factor (MCF)	0.9	DCCEE (2010)	0.79-0.90
Direct nitrous oxide emission factor	0.001	DCCEE (2010)	N.R
Ammonia emission factor	0.55	Midpoint based on range in Tucker et al. (2010)	0.40-0.70
Indirect nitrous oxide emission factor	0.01	DCCEE (2010)	0.002-0.05
N partitioning factor to sludge	0.23	Wiedemann et al. (2010)	N.R
P partitioning factor to sludge	0.9	Kruger et al.(1995)	N.R
K partitioning factor to sludge	0.05	Expert judgment	N.R

Farmer advisory group

This project was informed through the formation of a farmer advisory group to assist with selecting and prioritizing mitigation strategies. The advisory group was provided with background information on the carbon footprint of pork production and an outline of possible mitigation strategies. From this, mitigations were scored by each farmer. The scorecard rated options for their ability to reduce GHG emissions, how easily they could be implemented, their practical and economic feasibility, and other potential benefits such as participation in the CFI. Each option was then given a score out of 100. Table 8 shows the mitigation option rankings as determined by the farmer advisory group.

Table 8 – Mitigation options ranked by farmer advisory group

Mitigation Option	Ranking
CAP with destruction of methane using flare	70%
CAP with destruction of methane, with heat utilisation	70%
CAP with destruction of methane, with electricity generation	69%
CAP with destruction of methane, with combined heat and power production	68%
Reduction in feed wastage	58%
CAP with optimised effluent storage	52%
Carbon sequestration in trees	49%
Low GHG diets: Replacement of regular ingredients with by-products or waste products	46%
Optimised utilisation of effluent (fertiliser offset)	45%
Optimisation of commodity transport	42%
Low GHG diets: Low nitrogen diets	37%
Soil C sequestration	33%
Low GHG diets: Replacement of high GHG intensity ingredients with lower intensity alternatives	32%
Switching to deep litter grow-out systems	31%
Low GHG diets: New feed alternatives e.g. Algae	20%

GHG mitigation scenarios

Based on the recommendations from the farmer advisory group and from a scoping study of mitigation potential, we identified seven mitigation options to model. These were then grouped into four different scenarios combining different complementary mitigations. All mitigation scenarios incorporated a CAP-CHP, which had the greatest single mitigation potential of all options and was rated highly by the farmer advisory group. The mitigation scenarios were:

1) CAP-CHP with standard production.
2) CAP-CHP with optimised effluent storage and utilisation.
3) CAP-CHP with optimised diet (low GHG feed ingredients).
4) CAP-CHP with optimised diet, optimised effluent storage and utilisation, soil carbon sequestration and tree planting.

Detailed modelling assumptions are provided in Appendix A.

Results and Discussion

Carbon footprint

The baseline carbon footprint of the piggery was 4.86 kg CO_2-e/kg LW. Emissions were dominated by methane from the primary pond, followed by emissions from feed production and services. Throughout the supply chain, methane was the dominant GHG source, followed by carbon dioxide (Figure 5).

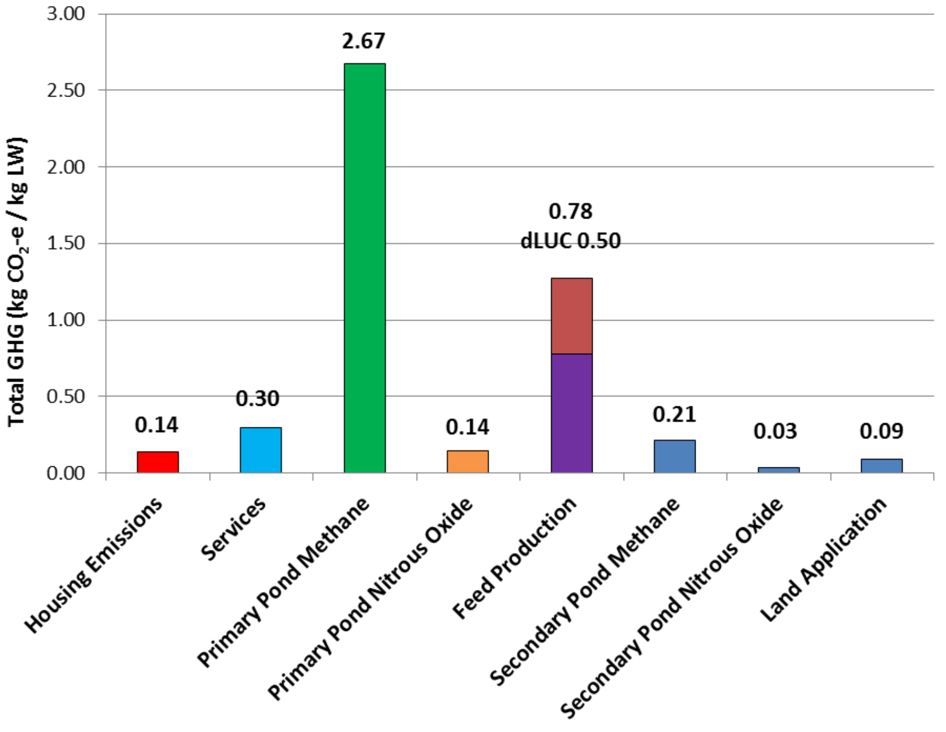

Figure 4 – Contributions to the carbon footprint of pork production at the farm gate for a conventional piggery in Victoria. Note: dLUC is direct Land Use Change GHG emissions

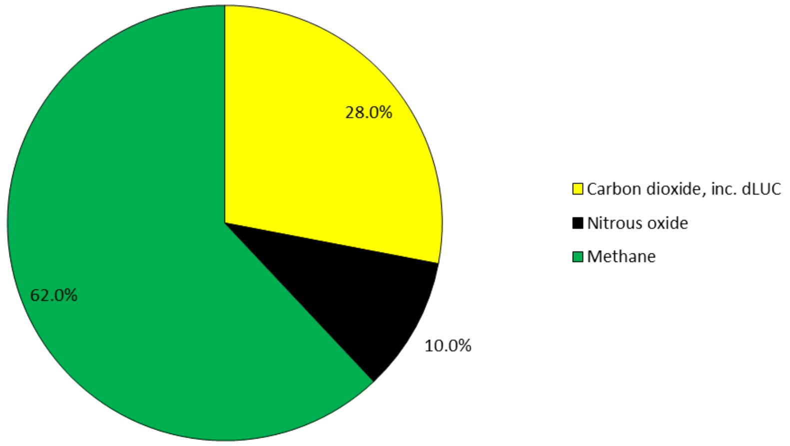

Figure 5 – Carbon footprint greenhouse gases for pork production at the farm gate for a conventional piggery in Victoria. Note: dLUC is direct Land Use Change GHG emissions

The results were reasonably similar to previous findings from Wiedemann et al. (2012, 2010) for Australian pork production, though the present case study included emissions from direct land use change, which weren't included in the precious studies. They confirmed the dominance of effluent treatment emissions in the carbon footprint for the case study piggery.

Mitigation scenarios

Total emissions from the mitigation strategies ranged from 0.6-2 kg CO_2-e/kg LW. The largest mitigation effect was from installing a CAP-CHP to destroy manure methane and generate power, which alone reduced emissions by 59%, or 2.8 kg CO_2-e/kg LW. The second most signficant mitigation strategy targeted high emission diet ingredients, and specifically imported soymeal, by replacing this with locally grown protein meals. This reduced emissions by 0.45 kg CO_2-e/kg LW. The emissions profiles are shown in Figure 6 and the contribution analysis is shown in Figure 7.

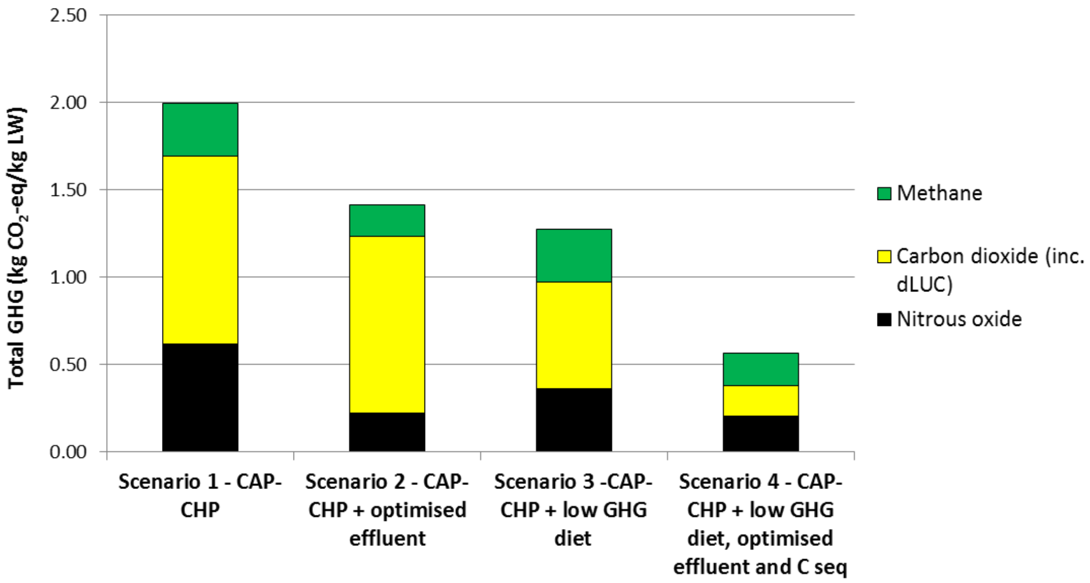

Figure 6 – Greenhouse gas emissions from four mitigation scenarios applied to a Victorian case study piggery. Note: dLUC is direct Land Use Change GHG emissions

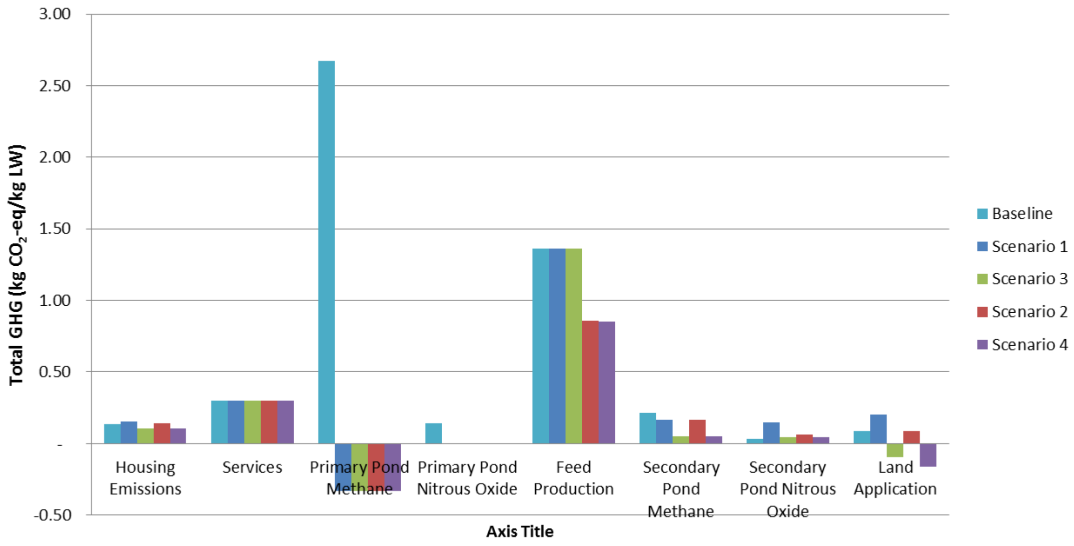

Figure 7 – Contribution analysis for four GHG mitigation scenarios s to the carbon footprint of pork production at the farm gate for a conventional piggery in Victoria

Qualitative cost-benefit analysis

There are a number of tangible and intangible benefits and costs associated with these mitigation scenarios. The most significant mitigation option is to install a CAP-CHP (or alternatively a digester). These systems can cost millions of dollars, and the payback period varies considerably depending on the design and the requirements for power and heat on site. For some piggeries, the payback may be less than 2 years, while for others it has been closer to 7 years (McGahan et al. 2012). Primarily, the payback comes from; sales of electricity, reduced on-farm energy costs, and sales of carbon credits under the CFI. As the CFI scheme is now in doubt, it is not clear what these credits will be worth in the future. A less tangible benefit arises from reducing odour. In areas where grid electricity supply is variable or not available, on-site power generation is a big advantage. Similarly, piggeries that have a higher energy demand (on-site feed mill, tunnel ventilation etc) will have shorter payback periods. One of the major disadvantages of these systems is the high initial capital investment required and there is potential for system failure, which can be costly.

Switching high GHG intensity feeds with lower GHG alternatives in combination with a reduction of the N content of the diet has the benefit of reducing manure management nitrous oxide emissions and reducing embedded emissions from feed. Considering diets are currently formulated on a ‘least cost’ basis, this is likely to cost more on average to achieve. Certainly the use of higher amounts of amino acids is likely to be expensive. Because the GHG reductions are more difficult to trace through the economy, this approach is unlikely to be subsidised by government carbon reduction programs.

Feeding by-products and waste products in replacement of typical feeds can reduce GHG emissions and may be cost effective for some piggeries. Cost effectiveness often depends on accessing product for no-cost with low costs for transportation. There is generally a higher degree of management required to

formulate rations with small amounts of by-products, particularly if these change often.
Optimised effluent storage involves direct irrigation of the treated effluent from the CAP for 70% of the year to reduce emissions from the pond. This approach assumes that effluent is stored mainly during wet periods of the year and irrigated directly (perhaps weekly) at most other times. This type of approach may require more management and therefore labour costs, particularly while in the set-up phase. Because there is less storage time and fewer losses, effluent is likely to have higher nitrogen levels. This may mean that lower volumes of effluent need to be irrigated to larger areas of land, which increases capital expenses. This is less of a problem in irrigation regions where effluent can be mixed with irrigation water.

The utilisation of effluent as a replacement for fertiliser has benefits in terms of GHG emissions, as it offsets the use of conventional fertilisers which have high embedded emissions. With rising energy costs and limited global reserves of P and K, fertiliser expenses are likely to continue rising. The major constraint for pig farmers is achieving good returns from these nutrients. Managing manure and effluent nutrients requires different expertise and more effort than using conventional fertilisers. In general, the return to the pig farm is low compared to the ‘true’ value of the nutrients. This may improve in time if equipment can be installed to capture fertiliser from effluent and produce a higher value product that can be used more like a conventional fertiliser. This is still some way off into the future at this stage. The greatest nutrient value is contained in piggery sludge, because this accumulates phosphorus at a high rate. Managing sludge applications as a replacement for super phosphate in grazing areas may be a way to reduce fertiliser requirements and to increase the value of the sludge.

Increasing soil carbon sequestration generally requires changing land management and maintaining that change for a long period of time (i.e. 100 years). This can be achieved by planting permanent pastures into old cultivation paddocks, particularly if these are run down from constant cropping and cultivation. There is a reasonable opportunity to increase soil carbon this way. However, the capital costs involved (land value) need to be taken into account. Pastures grazed by sheep or cattle also utilise only a small fraction of the nutrients that are applied by effluent, and this can result in nutrient management problems. This can be overcome by cutting pasture hay and selling this off farm to reduce nutrient loading. Provided there is sufficient suitable land available, there is a reasonable opportunity to increase soil carbon by using effluent and manure. On the case study farm, this could be achieved by arranging for effluent to be sold to nearby dairy farms, or by leasing land for pasture production to dairy farmers.

Tree planting can store reasonably large amounts of carbon per hectare, but in general the area of land required to substantially offset piggery emissions is too high to do this. None-the-less, tree planting around the piggery could be beneficial for improving visual amenity and helping to disperse odour.

Conclusions

Reducing the carbon footprint of pork production is an industry priority. Achieving this in practice will require reducing major emissions, and developing emission 'offsets' from the production system. This report provides a review of different GHG mitigation options available to piggeries. These were then tested through discussion with a farmer advisory group, and modelled for a case study piggery in Victoria. Some of the mitigations available to the industry include:

- Installation of CAPs or engineered digesters. This is the single most significant mitigation option available to the industry and has the potential to greatly reduce the carbon footprint of pork. By generating electricity to reduce on-farm use or for sale back to the grid, emissions are further reduced.
- The use of alternative "low GHG" feed rations. Feed inputs have a significant energy demand and associated direct GHG emissions. The use of "low GHG" feeds can offset the GHG emissions of the piggery. The costs are likely to be higher to achieve this though, and it is unlikely to attract government payments from the CFI or other government schemes.
- Emissions may be reduced by lowering the crude protein levels in pig diets. This may come at a higher cost, but in small improvements may be done cost effectively at times. This will lower GHG emissions from manure management.
- Decreasing feed wastage, while difficult to achieve, is an important efficiency measure that will reduce emissions from feed production and from manure management. This is more important when effluent is managed in open anaerobic lagoons.
- Reducing the retention time from secondary ponds, at least for part of the year, will also reduce emissions and will retain higher nutrient levels in effluent. Provided these nutrients can be used beneficially, this will result in lower emissions.
- The offset of fertiliser use through manure application to land. Nitrogen fertiliser manufacture uses large amounts of energy and is GHG intensive. Therefore, the use of manure in its place provides an offset for the emissions released during fertiliser production.
- Maximising carbon storage in effluent utilisation and sludge utilisation areas. This can be done by targeting soils that have been cultivated heavily in the past and converting these to permanent pastures or zero till cropping with additional effluent application.

We investigated the impacts of applying a range of these mitigation options to a conventional piggery in Victoria. The piggery carbon footprint (with standard rations and no covered ponds) was 4.86 kg CO_2-e/kg LW. We found that emissions could be reduced by 59% by installing CAP-CHP units to all the piggery sites. The farm has begun to implement this, with the first covered pond already in place and others to follow. Further reductions were achieved by reducing the CP level in the diets and selecting Australian grown protein meals, by reducing effluent storage time in secondary ponds and by improving the utilisation of effluent and manure nutrients. We found that carbon sequestration in soil would be achievable by planting permanent pastures in cultivation areas, though carbon would only be maintained while these pastures were in place. Reductions to the level indicated by the pork CRC (1 kg CO_2-e/kg pork) required application of several methods. The qualitative cost-benefit analysis showed that covering ponds may be cost effective for a reasonable proportion of the industry. Changes to effluent management may also be cost effective in some situations, particularly where other irrigation water is available. Other options such as modification of ration components or reduction of dietary CP is likely to increase costs and is less attractive.

This study has not covered every possible mitigation option, but selectively covered those thought to be most applicable by the farmer advisory group and the project team. Further investigation of mitigation strategies will be beneficial as the industry pursues this ambitious target.

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Appendix A

Modelling GHG mitigation options

Low GHG diets: Replacement of high GHG intensity ingredients with lower intensity alternatives

The diets were modified to account for the replacement of high GHG intensity ingredients with lower intensity alternatives. This meant replacing the soybean meal which is conventionally used at Australian piggeries with lower GHG alternatives. Australia imports soybean meal from three main countries; the USA, Brazil and Argentina. We assumed the proportions to be 40% from the USA and 50% from Brazil and Argentina with 10% supplied domestic production. To create the low GHG diets it was assumed that canola meal and Australian soybean meal replace the Australian market mix of soybean meal. It was assumed that this new component of the diet is comprised of 50% soybean meal and 50% canola meal. The canola meal amount has to be corrected for protein content.

Low GHG diets: Low nitrogen diets

Lysine was assumed to be the amino acid used as a protein supplement in the pig diets. It was assumed that for every 50 kg of soybean meal per tonne of feed, 1.93 kg of lysine and 48.07 kg of corn can be used as replacements. These amounts are based on the study by Cromwell (1996). This equates to 0.04 and 0.96 kg of each of these respectively per kg of soybean meal. This change in the dietary N corresponds to a 15-20% reduction in nitrogen excretion as reported by Cromwell (1996). For the purposes of this study, we assumed that the amino acid supplementation of the diet resulted in a 20% decrease in N excretion. Low nitrogen were assumed to be additional to replacing high GHG intensity ingredients with lower intensity alternatives. Therefore, the amount of soybean meal displaced can only be equivalent to amount of Australian soybean meal in the diet.

CAP with destruction of methane and combined heat and power with further treatment in a secondary pond

The MCF for the CAP in this study was assumed to be 65%. Recognising that there is a high degree of uncertainty in this factor, a 15% uncertainty range was applied (55-75%).

Nitrogen emissions from covered ponds were assumed to be negligible because of the impermeable nature of the pond covers. Nitrogen in the effluent stream was assumed to flow through the CAP to the secondary ponds, where losses were assumed to be equal to those reported in for conventional pond systems (Table 7). This resulted in the same level of nitrogen emissions for the covered and uncovered pond scenarios.

Hydraulic retention time in the covered pond was limited to 47 days to ensure pond sizes and construction costs were feasible. Volatile solids reduction was assumed to be 70% in the covered pond (including partitioning to sludge) resulting in 30% of initial VS flowing to the secondary ponds. Effluent was assumed to flow into uncovered storage ponds which were also assumed to operate anaerobically, resulting in further methane emissions.

Emissions from secondary ponds were calculated using a revised B_o and the standard MCF factor for covered ponds from the DCCEE (2010). The B_o of the effluent portion of the flow from the CAP was assumed to be partially digested, while the B_o of the waste feed was assumed to be digested completely. Therefore it was assumed that the B_o factor for effluent flowing to the secondary pond was reduced from 0.45 m^3 CH_4/kg VS to 0.12 m^3 CH_4/kg VS. Calculation of methane production/emissions from the covered and uncovered ponds is shown in Table 9.

Table 9 – Estimation of residual emissions from whole effluent treatment system

	Covered Pond	Uncovered secondary and tertiary ponds
VS excreted (whole herd, per finished pig - kg)	43.48	13.04 (flow from covered pond)
B_o (m^3 CH_4 / kg VS)	0.45 (0.38-0.52)	0.12 (0.10-0.14)
MCF (%)	65% (55-75%)	90% (80-90%)
Methane density (kg / m^3)	0.662	0.662
CH_4 generated (kg per finished pig)	8.42	0.94
VS reduction (inc. partitioning to sludge)	70%	40%
VS remaining (kg per finished pig)	13.04	7.9

CAP with destruction of methane and combined heat and power with optimised effluent storage and utilisation

Two additional elements were included in this scenario in addition to the CAP-CHP system; direct irrigation from the secondary pond for 70% of the year and high utilisation of nutrients from effluent for crop production, generating an emissions offset by replacing synthetic fertilisers in the crop production system.

The effluent is assumed to be irrigated directly from the CAP for 70% of the year, while for the remaining 30% it is treated in the secondary pond. This results in significant reductions in the amount of methane that is released to atmosphere. This is because the MCF of the effluent VS applied to land is assumed to be zero based on the study by Prapaspongsa et al. (2010).

For efficient use of effluent, the best management practices described by Wiedemann & McGahan (2011) were used as a basis for the emissions reduction potential. It was assumed that N losses were zero due to best practice implementation. Table 10 shows the “best management” nutrient substitution ratios used in this study.

Table 10 – Piggery nutrient by-product substitution ratios with fertiliser products

Nutrient	Substitution product	Piggery Sludge	Piggery Effluent
		Wiedemann & McGahan (2011)	Wiedemann & McGahan (2011)
Nitrogen	1 kg of nitrogen as Urea	0.8	0.8
Phosphorus	1 kg of phosphorus as Triple Superphosphate	0.8	0.8
Potassium	1 kg of potassium as Potassium Chloride	1	1

Soil carbon sequestration

Potential soil carbon sequestration rates were determined from the literature, with reference to the characteristics of the case study farm. The case study farm generated an estimated 914 t carbon, excreted annually in pig manure. This material is treated in the anaerobic pond system described, where the total mass loss is estimated at 70%. Carbon remaining for land application in the form of effluent or sludge is estimated to be 274 t annually. Total nutrients available for utilisation ranged from 80-180 t N depending on the loss assumptions used. Total phosphorus was 62 t and potassium was 57 t. Based on a sustainable application rate (including a provision for safe soil storage of nutrients) of 30 kilograms of phosphorus annually, the application area for the piggery effluent was 104 ha. This resulted in a carbon application of 0.88 t C/ha.yr and 207 kg N. We assumed application to stable, irrigated perennial pasture for grazing and assumed a total irrigation period of 20 years prior to establishing a new irrigation area. We assumed carbon sequestration at a rate of 1 t C/ha.yr based on the C inputs and the additional grass production resulting from nitrogen additions. Provided land remained under perennial pasture, we assumed sequestration would be permanent and that new irrigation blocks could be established every 20 years.

Additional carbon and nutrient applications are made with sludge approximately every ten years when ponds are desludged. At this time, a total of 1830 t of carbon is applied to land. Sludge contains high levels of phosphorus, which limits applications to relatively low rates. We assumed sludge applications were 1.25 t DM / ha, providing a capital application of 50 kg P. This gave an application of 0.15 t C / ha and 35 kg N, applied over an area of 11,800 ha every ten years. We assumed an additional level of carbon sequestration of 0.1 t C/ha from the application of sludge.