AUSTRALIAN EGG CORPORATION LIMITED

Environmental Assessment of an Egg Production Supply Chain using Life Cycle Assessment

Final Project Report

A report for the Australian Egg Corporation Limited

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Foreword

Environmental management is an important focus area for the Australian egg industry. Modern production systems have led to continual productivity improvements across the industry, which will in turn result in a high degree of environmental efficiency. This project demonstrates the efficiency of Australian egg production with respect to three important environmental and resource efficiency issues: global warming, water use and energy use. This is the first study of its type for the Australian egg industry and establishes a performance benchmark for the future.

This project was funded from industry revenue which is matched by funds provided by the Federal Government.

This report is an addition to AECL's range of research publications and forms part of our R&D program, which aims to support improved efficiency, sustainability, product quality, education and technology transfer in the Australian egg industry.

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Abbreviations

ABS .... Australian Bureau of Statistics
CED .... Cumulative Energy Demand
CH_4 .... Methane
CO_2-e .... Carbon Dioxide Equivalent
CPRS .... Carbon Pollution Reduction Scheme
DCCEE .... Department of Climate Change and Energy Efficiency
FCR .... Feed Conversion Ratio
FU .... Functional Unit
GHG .... Green House Gases
GWP .... Global Warming Potential
IPCC .... Intergovernmental Panel on Climate Change
LCA .... Life Cycle Assessment
LCI .... Life Cycle Inventory
MJ .... Mega Joule
ML .... Megalitre
PAS .... Publically Available Specification
N .... Nitrogen
N_2O .... Nitrous Oxide
NGERS .... National Greenhouse and Energy Reporting System
NGGI .... National Greenhouse Gas Inventory
P .... Phosphorus
TS .... Total Solids
VS .... Volatile Solids
VW .... Virtual Water
WF .... Water Footprint

Executive Summary

The Australian egg industry is characterised by intensive, modern, highly efficient production systems and a growing free range production sector, which together produce some 345 million dozen eggs annually. The industry aims to have a high degree of environmental performance through adoption of best management practices for a range of environmental issues although, to-date, there have been no comprehensive analyses of environmental performance across the whole egg supply chain. In order to quantify the most important environmental and resource impacts faced by the industry, a life cycle assessment (LCA) study was commissioned to investigate emissions of greenhouse gases, energy and water use. This study investigated both caged and free range egg production through to the end of the primary production supply chain, using a functional unit of one kilogram of eggs produced.

Australian egg production was found to generate low levels of greenhouse gas (GHG) when compared with egg production from European studies. Total GHG was 1.3 +/- 0.2 kg CO_2-e / kg eggs from caged production and 1.6 +/- 0.3 kg CO_2-e / kg for free range production. Despite the overlapping confidence intervals, free range production generated higher emissions than caged production when shared variability was taken into account.

Cumulative energy demand (CED) for caged production (0.7 +/- 0.9 MJ / kg eggs) was lower than studies previously reported in the literature. Cumulative energy demand for free range egg production (13.1 +/- 1.1 MJ / kg eggs) was slightly higher than for caged production, but was similar to other studies reported in the literature.

The higher impacts for GHG and CED associated with free range production were attributable to higher feed conversion ratio (FCR) and lower productivity compared to caged production.

The relative environmental efficiency of egg production in this study arose from the high performance of modern Australian egg production coupled with the low input nature of Australian grain production. Additionally, Australian grain is produced in conditions that do not favour nitrous oxide emissions, which is reflected in the lower emission factor recommended for use in the Australian inventory (DCCEE 2010). These result in low GHG and energy use for Australian eggs, both in the caged and free range systems.

Few studies were found in the literature that investigated water usage. Water use was calculated using three approaches. Of these, ABS water use (17.4-17.5 L / kg eggs) is most easily comparable and understandable figure, being a reasonable estimate of the industries' competitive water use. Further impact assessment for water use was not carried out.

The study identified green water as the major contributor (95-96%) to the total water footprint (WF) for Australian eggs. Considering this, the WF for eggs is clearly not a good measure of the egg industries' impact on competitive water uses in Australia, or of the environmental impacts of water use. The ABS or blue water use volumes are more comparable to other agricultural or urban water uses.

The contribution analysis showed that feed grain production and use was the largest impact source, followed by on-farm water and energy use, and manure management (for GHG only).

Consequently, mitigation strategies and efficiency measures that reduce feed use would be highly beneficial to the industry. However, considering the high degree of feed efficiency achieved to date, substantial further gains are expected to be more difficult to achieve.

Reducing farm electricity use is another attractive mitigation strategy for the industry that will lead to lower energy use, lower GHG and lower costs, provided production levels can be maintained.

Emissions from manure management were estimated using the default values provided by the IPCC (Dong et al. 2006). These were found to allow a greater degree of flexibility than the Australian tier 2 methodology (DCCEE 2010). Results from the DCCEE scenario were similar to results based on the IPCC, despite the omissions and likely errors in the DCCEE methodology. Further research into manure management and emission factors would be warranted to improve estimation methods.

Based on the results of this study, the following recommendations are provided:

1. Further investigation of Australian feed grain systems is required to improve the quality of LCI data for the egg production system. Because of the large contribution of ration production to the egg supply chain for GHG, energy and water use, this should be seen as a high priority for the industry in collaboration with other animal industries.
2. A broader spectrum of egg producers from other production regions are required to deliver results that could be considered representative of the whole Australian industry.
3. Mass balance research is required to quantify mass flows, excretion and emission rates from modern cage and free range production facilities. The highest priorities in this area are:
   - updated emission factors from manure application;
   - updated ammonia emission factors for layer sheds;
   - updated nitrous oxide emissions from layer sheds;
   - manure reuse and mass flow research to update and improve the flexibility of the DCCEE methodology, particularly for free range systems; and
   - updated ammonia, nitrous oxide and methane emissions from stockpiles.
4. Collection of energy and water benchmarking data across a greater cross section of the industry is required. These data will provide a robust basis for targeting industry improvement and could be integrated into future LCA studies.

1. Introduction

1.1. Environmental Assessment of the Egg Supply Chain

The Australian egg industry is characterised by intensive, modern, highly efficient production systems and a growing free range production sector. The industry produces eggs for the domestic market from farms located in all states of Australia, with major production centres in New South Wales, Queensland and Victoria. The Australian layer flock totals 20.1 million hens, producing in the order of 345 million dozen eggs annually (AECL 2010).

The industry has undergone a major re-structure in the past five years to address new welfare regulations for layer cages, which has resulted in a high proportion of the industry changing over to environmentally controlled housing with manure removal via a belt system. These housing systems will be described in this report as ‘environmentally controlled housing’. Concurrently, the free range sector has expanded (and continues to expand) in response to strong consumer demand for free range eggs. Currently approximately 63.5% of Australia’s egg production is from caged systems and 26.6% is from free range systems. The remaining production is from barn-laid and organic systems (AECL 2010).

The industry recognises its responsibility to manage resources and environmental impacts in a responsible fashion, and has set environmental priorities to improve performance in the key areas of water and energy usage and greenhouse gas (GHG) emission intensity. These areas are in line with national environmental priorities and are also of interest to the general public. However, research has not been conducted to quantify these areas of resource use and emission across the Australian egg supply chain. This knowledge gap led to the commissioning of a life cycle assessment (LCA) project for the industry. LCA is a tool used world-wide to determine the resource use and environmental impacts for a product of interest, by assessing the whole life cycle of a product. LCA is a robust method for determining resource usage and impacts, and can be reported in an easy to understand form by using the concept of a ‘footprint’ for carbon, water or energy of a product such as eggs.

1.2. Project Objectives

The egg industry commissioned this project with the following objectives:

1. Assess the eco-efficiency of an Australian egg production system using LCA
2. Quantify water and energy use, and GHG emissions from an Australian egg production system.
3. Determine key areas in the egg supply chain where improvements can be made to reduce resource usage and environmental impacts, and identify areas of further research.
4. Identify the applicability and implications of environmental regulations (particularly the proposed Carbon Pollution Reduction Scheme – CPRS) on the egg industry.
5. Develop a basic water and energy usage dataset for benchmarking resource usage performance.

6. Develop extension materials that will convey the key messages from the research back to the industry.

The project was carried out in several stages which have been reported separately:

Stage 1:	Project Scoping Study – Milestone report 2
Stage 2:	Collection of benchmarking data and investigation of industry exposure to energy and GHG regulations – Milestone report 3
Stage 3:	Extension of benchmarking results to the industry – Fact sheet development
Stage 4:	Life Cycle Inventory data collection and collation – Milestone report 5
Stage 5:	LCA Modelling and investigation of implications for the industry – Final report (this report)

1.3. Greenhouse Gas Emissions in Agriculture

'Greenhouse' gases refer to a group of compounds that contribute to energy capture in the atmosphere surrounding the earth, the so-called 'greenhouse effect'. Several gases contribute to this effect, with the primary gases being water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3). In addition, there is a range of human-made halocarbons (such as perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) that exist in small amounts, albeit with high potency. These greenhouse gases occur only at trace levels in the atmosphere, making up only 0.1 per cent of the atmosphere by volume (IPCC 2001).

The greenhouse effect is vital for life on earth; however, alterations to the concentration of these gases may lead to warming of the atmosphere and subsequent changes to the earth's climate. Climate change in Australia will lead to increased rainfall variability and higher temperatures, placing pressure on agricultural production systems and leading to volatility in supply of commodities such as grain. This has important ramifications for the egg industry. Hence, any contribution the industry can make to reducing greenhouse gas emissions is important for the long term viability of the sector.

In 2008, agriculture contributed 87.4 Mt CO_2-e (15.9%) of Australia's GHG emissions, making it the second largest emitting sector behind stationary energy (DCCEE 2010). Contributions from agriculture are from animal, soil and manure sources (methane and nitrous oxide) and do not include CO_2 from energy usage. However, emissions from agriculture have been in decline for the past 18 years while most other sectors (particularly stationary energy) reported significant increases in this period (DCCEE 2010).

Greenhouse gases contribute to atmospheric warming at different rates. Hence, a scale has been developed to compare gases based on their warming potential (global warming potential – GWP) relative to carbon dioxide. This compares the radiative forcing from a given mass of a greenhouse gas to the radiative forcing caused by the same mass of carbon dioxide and is evaluated for a specific timescale. Global warming potential depends both on the intrinsic capability of a molecule to absorb heat, and the lifetime of the gas in the atmosphere. Global warming potential values take into account the lifetime, existing concentration and warming potential of gases and vary depending on the time period used in the calculation. Global warming potential is used under the Kyoto Protocol to compare the magnitude of emissions and removals of different greenhouse gases from the atmosphere. The GWP of the four major greenhouse gases and two groups of gases (HFCs and PFCs) is shown in Table 1. The GWP of each greenhouse gas is expressed in carbon dioxide equivalents (kg CO_2-e).

Table 1. The global warming potential of major greenhouse gases

Greenhouse Gas	Lifetime in the atmosphere (years).	100 year global warming potential – IPCC 2007	100 year global warming potential – DCCEE (2010)
Carbon Dioxide	Variable	1	1
Methane	12	25	21
Nitrous Oxide	114	298	310
Sulphur hexafluoride	3,200	22,800	23,900
HFCs	1.4 - 270	124 – 14,800	1,300-11,700
PFCs	740 – 50,000	7,400 – 17,700	6,500-9,200

Source: IPCC 2007 – Solomon et al. (2007)

Because of the requirement for Australia to report against the Kyoto emission benchmarks, the DCCEE (2010) uses GWP values from earlier IPCC recommendations that have now been replaced. This study used the GWP values recommended by the IPCC 2007 except for the DCCEE (2010) scenario.

GHG Emission Reporting

Greenhouse gas emissions, particularly those from agricultural sources, are difficult and expensive to measure. They also have a high degree of temporal and spatial variability. Consequently, most GHG emission reporting frameworks depend on estimation methods rather than real-time measurement. Although there are a finite number of measurable emission sources, there are multiple ways in which these emissions can be aggregated and reported. At the broadest level, the IPCC calculates emissions for the whole planet based on GHG inventories from each nation. Australia publishes annual emission figures and a methodology for estimating these emissions annually.

National Greenhouse Gas Inventory

The Australian National Greenhouse Gas Inventory (NGGI) is constructed using data collected from every industry that contributes to emissions. Emission estimation techniques and formulas have also been developed, and these are reported in a series of manuals (referenced throughout this document as the DCCEE 2010). The NGGI methods are the basis for GHG research in Australia, though because of the broad nature of the NGGI, methods are often simplified for smaller emitting industries such as the egg industry.

Because each national inventory around the world is used to create a global estimate of GHG, there is a necessary degree of standardisation in the methods used. This standardisation process is overseen by the Intergovernmental Panel on Climate

Change (IPCC). The IPCC also publish a comprehensive emission estimation manual to be used as an international reference for developing a NGGI. Australia's NGGI manuals have been developed from the IPCC, with country specific information in some sections.

Business Carbon Accounting

A separate framework has been developed for accounting for GHGs in the business sector. This framework has been developed in response to efficiency targets, either internal targets established by a company or regulatory targets established by the Government. The business framework classifies emissions into a number of categories, including:

- emissions that arise directly from the business (Scope 1 emissions);
- emissions that arise off-site as a result of business energy usage (Scope 2 emissions); and
- emissions that are generated because of products or services used by the business (Scope 3 emissions).

Of these emission sources, scope 1 and 2 emissions are considered directly attributable to a company, while scope 3 emissions are generally not included because they are considered the result of another business.

This framework has been used to develop the National Greenhouse and Energy Reporting System (NGERS), legislated under the National Greenhouse and Energy Reporting Act. Importantly, emissions arising from agricultural sources (such as emissions from livestock or manure) are not included. Further explanation of this framework with respect to the Australian egg industry has been provided in the Milestone report 3 for this project.

Life Cycle Assessment

Life cycle assessment is a third system for aggregating emissions, devised with a specific focus on products and services. This system investigates the production supply chain required to produce a given product or service, and aggregates emissions from every source throughout this whole supply chain. This may cover a number of business structures and includes all sources of GHG. Another term used to express a similar approach is the 'carbon footprint' (CF) of a product. This has become a popular term for a study that only investigates GHG emissions, and generally employs a LCA methodology approach (i.e. PAS 2050). As such, LCA results can be reasonably termed carbon footprint results. It should be noted however, that carbon footprint results should always be carefully reviewed to ensure that a rigorous, comprehensive methodology (such as PAS 2050) was applied to generate the results. Without this, carbon footprint results are unreliable.

Summary

Greenhouse gas data are estimated and reported in a number of ways for Australian industries, businesses and products. It is important to note that the results collated under one system are not comparable to a different system. For example, LCA results cannot be used to determine business emissions that would be reportable under the NGERS, nor can they be used to approximate the egg industry's contribution to the NGGI. For this reason it is important that GHG results include a clear explanation of the system under investigation and the methods used for estimating emissions, together with any exclusions from the calculations.

1.4. Water Accounting in Agriculture

As with GHG estimation, water usage can also be calculated using a variety of definitions and methods, resulting in highly variable results for water use from agricultural products. This has also resulted in confusion in the general public because information is commonly quoted from very different sources. For example, it is reported that agriculture uses up to 83% of available water in the Murray Darling Basin (ABS 2008), and then at the product level it has been reported that eggs use 1,844 L / kg Australian eggs produced (Hoekstra & Chapagain 2007). To the casual reader, it appears that the contribution of egg production to total water use in the Murray Darling Basin could be roughly calculated as follows:

Total Australian egg production = 345 M dozen x 0.7 kg / doz = 241,500,000 kg eggs annually.

Total water use = 241,500,000 x 80% (estimate of eggs produced in MDB) x 1,844 L / kg eggs = 356,261 ML.

To place this value in context, this volume of water use would be roughly 5% of total agricultural water use in the MDB as reported by the ABS (2008). This is roughly one-third of the water used by irrigating industries such as cotton and rice (compared to data from ABS 2008).

However, when the methods used to determine these two figures are examined it is clear that the 'water used' to produce agricultural products is very different to the 'water used' by agriculture at the nation-wide level. In fact, research in the beef industry has shown that as little as 0.5% of the water reported for producing beef by some literature sources can be compared to the water use estimates developed by the ABS for Australian agriculture (Peters et al. 2010b). Considering the disparity in the results, it is clear that methods must be developed to clarify the meaning of the term 'water use', particularly at the product level.

Defining water use is further complicated by the temporal and spatial characteristics of fresh water as it moves within the global water cycle. Water is rarely completely alienated, at a global level, from this sphere indefinitely and is therefore not 'used' in the same sense as energy resources are. In this sense, water is a renewable resource. However, at any given time there is a limited resource of fresh water available on the earth for short-term competitive uses, because of the practical limitations to storage of fresh water (which may be a period of months up to several years). Of the available water, there are also large differences in the degree of natural replenishment of the water source and the degree of transferability between some sources, making comparison meaningless without separate classifications.

Definitions and Classification of Water Use

Blue and Green Water

The primary distinction between water assessment methods revolves around the handling of water derived from rainfall used for plant production. Studies that follow a virtual water (VW) or water footprinting approach include water that is utilised for plant production from rainfall in addition to water used from groundwater aquifers, dams or rivers. To clarify the contribution of water from these sources, two terms have been introduced by Falkenmark (2003). **Blue water** represents the general understanding of liquid water, i.e. water that may be sourced from surface or groundwater supplies. **Green water** is classed as evaporation and transpiration (or evapo-transpiration) water used in cropping, derived directly from rainfall (i.e. Falkenmark 2003, Falkenmark & Rockstrom 2006). These definitions have been adopted as the standard approach to water footprinting (Hoekstra et al. 2009b); however, few water footprint studies have been completed since this differentiation was introduced.

Classification of Blue Water

Prior to the introduction of the virtual water concept, 'blue' water was the only source of water commonly discussed in the field of water management and engineering. The supply and use of fresh water is a critical issue for agriculture, industrial, domestic and environmental uses in Australia and internationally. Because of the spatial and temporal characteristics of water, a number of further classifications have been proposed. These help to differentiate between sources that are replenished fairly rapidly (i.e. a river system) and sources that are replenished very slowly (i.e. the artesian basin). Additionally, differentiation of 'uses' into consumptive (such as evaporative) and non-consumptive (i.e. driving turbines for hydro-electricity generation) is useful.

A system of classification for different water uses and sources was developed by Owens (2002). The primary classifications include:

- **Water consumption** or consumptive use. Off-stream water use where water release or return does not occur (i.e. evaporation from storage, respiration / transpiration / evaporation of drinking water after it is consumed)
- **Water depletion**. Withdrawal from a water source that is not replenished or recharged (i.e. a water deposit).

Owens (2002) presents five water use and water depletion indicators:

- In-stream water use indicator (i.e. the quantity of water used for hydro-electric power generation);
- In-stream water consumption indicator (i.e. evaporative losses from storages and canals in excess of unrestricted river losses);
- Off-stream water use indicator (i.e. surface withdrawals from sustainable sources that are returned to the original basins and groundwater withdrawn from sustainably recharged aquifers and returned to surface waters);
- Off-stream water consumption indicator (i.e. evaporative losses and other conveyance losses, and transfers to another river basin); and
- Off-stream water depletion indicator (i.e. withdrawals from overdrawn, unreplenished groundwater sources).

These provide a clear and sensible distinction between consumptive and non-consumptive uses, and highlight the difference between replenishing and non-replenishing sources.

Water Footprint Method

Water footprinting was derived from the virtual water (VW) concept, which was first proposed in the late 1990s. Allan (1998) first used the term 'virtual water' to describe the water required to produce tradable commodities (particularly food) in water stressed economies. The VW method makes a useful contribution to the global understanding of water transferability by showing that irrigation water in one region can be saved by importing food that would need to be grown using irrigation water in that region, thereby reducing stress on local fresh water resources. Because the basic physiological water requirements for crops can be met by either irrigation (blue water) or green water in other production regions from which food may be purchased, these sources were not differentiated in initial VW studies.

The term water footprint (WF) was first used almost interchangeably with VW by Chapagain and Hoekstra and has become a clearly defined method for determining water use associated with food products and trade (Chapagain & Hoekstra 2003, Chapagain et al. 2006, Hoekstra & Hung 2002, Hoekstra & Hung 2005). These early studies did not differentiate between blue and green water sources. The virtual water use or water footprint of a range of agricultural products has been compiled by Hoekstra and Chapagain (2007). Results from these authors are presented in Table 2.

Table 2. Virtual water or water footprint estimates for a range of agricultural commodities

Species	L / kg (Australian estimates)	L / kg (World average)
Eggs	1,844	3,340
Chicken meat	2,914	3,918
Pork	5,909	4,856
Sheep meat	6,947	6,143
Beef	17,112	15,497
Soybeans	2,106	1,789
Wheat	1,588	1,334
Soybeans	2,106	1,789
Sorghum	1,081	2,853

Source: Hoekstra & Chapagain (2007)

Terminology to differentiate between blue, green and grey water use was adopted by the water footprinting methodology (see Hoekstra et al. 2009a). Prior to this, VW/WF results had, on some occasions, lead to erroneous conclusions, particularly where the WF was considered synonymous with water extracted from a river or ground water source. In reality, the majority of the WF for agricultural products in Australia is sourced from green water, which has very different opportunity costs and impacts when compared to blue water.

Water footprint estimates are typically determined retrospectively using models to estimate crop water use (evapotranspiration) and livestock requirements. Water use data may be collected from a number of different sources depending on availability. The most broadly reported WF data were collated from a global study of water transfer with trade (see Chapagain & Hoekstra 2003). Water footprinting allows for a degree of flexibility in the models or processes used to collate the water inventory, and specific methods used in this study are discussed further in section 4.3 of this report. These methods integrate the definitions and classifications described in the preceding section.

ABS Water Use Method

The ABS collates water use data for major water users within Australia using a series of definitions and methods that have been developed with a focus on water sources that are used competitively (i.e. river water, groundwater etc). The ABS only considers blue water sources and can be considered as a sub-category within the broader water footprint of a product. However, the ABS method is a useful measure of competitive water use within the Australian context. Applying this method allows a degree of comparability between measures.

The ABS defines water use as 'the sum of distributed water use, self-extracted water use and reuse water use'. 'Distributed' and 'self-extracted' water uses are defined as water supplied from engineered delivery systems. Delivery systems vary greatly in size and degree of infrastructure, incorporating a range of systems, from sub-artesian groundwater extraction to water supply from rivers or state-owned dams.

Water is classified as 'distributed' if the water is purchased, or 'self-extracted' if not. Water is identified as being drawn from either a surface or groundwater source.

The water use inventory developed by the ABS does not generally include some water sources used for agriculture, such as water sourced from farm dams. Water is also considered as 'used' once it is extracted. For most agricultural purposes extracted water will be a consumptive use, because water is typically used in evaporative processes for crop or livestock production.

Preferred Water Accounting Methods

For the purposes of this study, three methods have been used to estimate 'water use', with reference to the definitions and classification systems described. The first of these is the water footprint method, with differentiation of blue and green water use.

The second is the Australian Bureau of Statistics (ABS) method which is used for generating Australian water use statistics and the third is 'Consumptive fresh water use'. The difference between the ABS and consumptive fresh water categories are described in Table 3.

Table 3. Volumetric water use categories used in this project

Water use reporting category	Units	Description	Noted exclusions of relevance to this project
ABS Equivalent Water Use	ABS Equiv. L	All Australian water uses from extracted sources (surface water, bore water etc) including water withdrawals released to sewer (meat processing)	Water use drawn from small on-farm storages and evaporation from these storages Consumptive or non-consumptive embedded water flows from other countries
Consumptive Fresh Water Use	L	Consumptive uses from direct capture of run-off in on-farm storages, including storage evaporation All consumptive water uses including embedded water flows from other countries.	Withdrawals of water released again to sewer (specifically associated with meat processing)
Blue Water Use	L	All consumptive uses, equivalent to Consumptive Fresh Water Use in this study	
Green Water Use	L	Plant uptake of soil stored moisture from rainfall	
Water Footprint	L	Blue Water Use + Green Water Use	

2. Literature Review

2.1. Life Cycle Assessment in Agriculture

Life cycle assessment was developed in Europe in the 1960s, primarily as an environmental tool for use with the industrial sector. In more recent years, LCA has been applied to the agriculture industry in response to the growing demand for information about food products and supply chains. This shift has led to a greater degree of complexity because of the dynamic, open nature of agricultural systems. This has led to on-going methodology development to ensure accurate assessment.

A number of LCAs have been completed for Australian agricultural industries over the past 10 years, including major studies for dairy (Lundie et al. 2003), red meat (Peters et al. 2010a, Peters et al. 2010b) grains (wheat, barley, canola - Narayanaswamy et al. 2004 and maize - Beer et al. 2005) and pork (Wiedemann et al. 2010). Additionally, Ridoutt et al. (2009a, b) have published work on water footprinting for the Mars group in Australia covering several agri-food supply chains. Other private work has been carried out for some industries but these are not available in the public literature.

Internationally, many studies have been completed for a range of agricultural production systems. Of these, the greatest numbers have been completed for dairy products (Basset-Mens et al. 2009, Casey & Holden 2005, Cederberg & Mattsson 2000, de Boer 2003, Eide 2002, Haas et al. 2001, Hospido et al. 2003). Additionally, a number of studies have been conducted for beef (Beauchemin et al. 2010, Casey & Holden 2006, Nguyen et al. 2010, Verge et al. 2008), meat chickens (Prudencio da Silva Jr. et al. 2008, Katajajuuri et al. 2008, Pelletier 2008) and pork (Basset-Mens & van der Werf 2005, Dalgaard et al. 2007).

Two studies (Cederberg et al. 2009, Williams et al. 2006) covered all of the above species, together with egg production.

LCA Studies of Egg Production

The literature review identified six detailed egg LCA studies (Cederberg et al. 2009, Dekker et al. 2008, Mollenhorst et al. 2006, Sonesson et al. 2008, Verge et al. 2009, Williams et al. 2006) and one study of egg packaging (Zabaniotou & Kassidi 2003). These studies investigated a number of different production systems including caged, aviary, free range and organic production systems, though only results from cage and free range systems were covered in the review.

All studies investigated total GHG and four studies investigated energy use. No studies reported water use.

Five studies were from Europe and one study (Verge et al. 2009) was from Canada. One study, (Cederberg et al. 2009) was based on the earlier work by Sonesson et al. (2008); however, both studies have been included in the review because of the different emphasis and information provided in each.

Table 4 provides a summary of these studies including main production parameters and results.

Table 4. Summary of international LCA research for egg production

Reference	Study country	Production system	Egg Production data	Functional Unit	GHG (kg CO_2-e / kg eggs)	Main contributor to total GHG	Contribution analysis for total GHG	Energy Use (MJ/kg eggs)	Main contributor to energy use
Mollenhorst et al. (2006)	The Netherlands	Multiple systems. Cage and free range reported here.	NR	1 kg eggs	3.9 (cage) 4.6 (free range)	Feed production = 78-82%.	Not reported.	0.0013 – 0.0014 [a]	77-84% feed production
Williams et al. (2006)	UK	Multiple systems. Cage and free range reported here.	eggs / bird / yr = 295 (cage), 289 (free range)	20,000 eggs (1 t). Reported here **per 1 kg eggs**	5.25 (cage) 6.18 (free range)	NR	N_2O = 52%[b] CO_2 = 44%[a] CH_4 = 4%[a]	13.6 (cage) 15.4 (free range)	NR
Dekker et al. (2008)	The Netherlands	Organic free range with two shed types – single and multi-tiered.	eggs / bird / yr = 276	1 kg eggs	4.0 (organic)	Feed production = 75%	N_2O = 77% CO_2 = 21% CH_4 = 3%	13.1	62% feed production, 33% transportation
Cederberg et al. (2009)	Sweden	Multiple systems – 38% cage, 56% free range, 6% organic.	20 kg / hen to 72 wks (approx. 300 eggs/hen/yr)	1 kg eggs	1.4 (national average)	Feed production = 85%	N_2O = 56% CO_2 = 39% CH_4 = 4%	NR	NR
Sonesson et al. (2008)	Sweden	Two caged egg farms.	Hens housed for 58-60 wks, 20.2 - 22.5 kg eggs / hen	1 kg eggs, including packaging, includes retail	1.6 - 1.8 (cage)	Feed production = approx. 66-72%	N_2O = 45% CO_2 = 50% CH_4 = 5%	17.3-18.7 MJ/kg	approx. 47-56%
Verge et al. (2009)	Canada	Cage, some with liquid manure handling.	eggs / bird / yr = 186	1 dozen eggs (assume 700g). Reported here **per 1 kg eggs**	2.47 (cage)	Feed production	N_2O = 54% CO_2 = 35% CH_4 = 10%	NR	NR

[a] values originally presented in kJ/kg egg. Considering the very low values compared to other studies these values may be subject to a reporting error in the original reference.
[b] Values interpolated from results spreadsheet released with the project – not directly reported

Production Efficiency

Production efficiency factors influenced environmental efficiency between the different studies. Specifically, differences in feed conversion ratio (FCR) have a strong bearing on results because of the high burdens associated with feed production. Egg production per hen also effects efficiency because of the inputs and emissions associated with breeding and pullet production. Bird production data were presented for three studies and are reported below along with industry targets set by Hy-line Pty Ltd, a major supplier of layer hen genetics in Australia (see Table 5).

Table 5. Reported production parameters for layer hens in three European LCA studies and comparative production targets from an Australian layer hen genetics supplier

Production Parameter	Units	Dekker et al. (2008) (organic free range)	Williams et al. (2006) (cage)	Cederberg et al. (2009) (mixed cage and FR)
Weeks housed	Weeks	44	55	58-60
Egg Production	eggs/hen/yr	276	295	297-320[a]
Mortality rate (over length of the flock)	%	13	5	3.8 – 6.2%
FCR[b]	-	2.7	2.4	2.1[c]

[a] This number accounts for mortalities – defined as eggs / hen housed.
[b] Calculated from egg production, assuming 63 g / egg, and feed intake data.
[c] This figure is different to the FCR value reported by Hy-line (2006) of 1.96 – which is calculated from 21-74 weeks.

Contribution Analysis

All studies identified feed production as the major source of GHG and energy usage for egg production. Emissions from feed production were mainly driven by nitrous oxide. Energy usage (housing, transport etc) was found to be the second largest contributor to GHG in most studies, while manure management contributed a relatively smaller proportion of GHG.

For studies where GHG emissions were disaggregated, nitrous oxide was reported to be the primary GHG in all but one study (Sonesson et al. 2008). Nitrous oxide emissions were mainly associated with feed grain production and manure management (including indirect nitrous oxide from ammonia emissions).

Carbon dioxide from fossil fuel use was the second largest contributor to total GHG. Carbon dioxide was primarily related to the use of fuel for grain production and, secondly, to the use of energy for heating or cooling of layer hen houses. The studies identified minor contributions of methane, all of which was derived from manure management.

GHG Emission Estimation Methodology

Estimation of GHG emissions from crop production and manure management in most studies was done using emission factors supplied by the IPCC (tier 1 or 2 methods), from either the 1996 or 2006 manuals, together with local data or literature values to improve the estimation of manure excretion. Two studies (Dekker et al. 2008; Mollenhorst et al. 2006) used literature values to estimate manure emissions.

Comparison of Production Systems

Mollenhorst et al. (2006) and Williams et al. (2006) presented data comparing alternative production systems, including cage housing, deep litter (barn housing), free range and free range organic. In both studies, cage production systems were more efficient with respect to GHG and energy usage per kg of eggs. This was mainly related to the superior production efficiency (particularly FCR) for cage hens compared to free range or organic hens.

3. Methodology

An LCA project comprises four parts:
i) goal and scope definition;
ii) inventory analysis or LCI;
iii) impact assessment; and
iv) interpretation.

These stages are outlined in Figure 1 below. Goal and scope definition is the first step in conducting a LCA and 'frames' the whole project. As can be seen in Figure 1, the stages are interactive and dynamic.

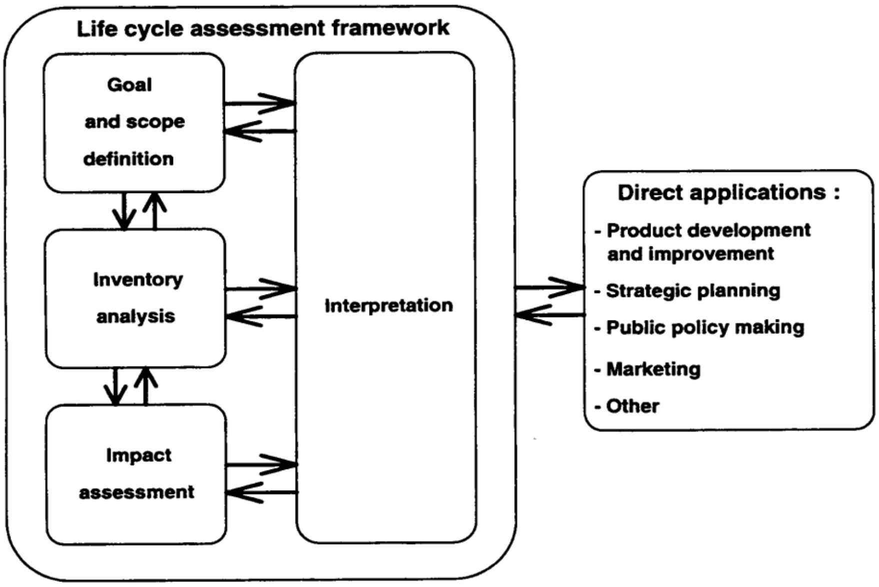

Figure 1. Life cycle assessment framework (ISO 14040:2006)

3.1. Goal

Application

The present study was commissioned with the following aims:

1. To provide indicative environmental impact data for Australian egg production to the general public;
2. To identify environmental research priorities throughout the supply chain by identifying and quantifying impact 'hotspots' for GHG emissions;
3. To identify the environmental impacts of different production systems (i.e. free range compared to cage production);
4. To establish an industry benchmarking baseline for resource usage and environmental performance;
5. To identify key areas of the supply chain where further monitoring of performance should be undertaken to improve performance; and
6. Establish a process of data collection and assessment that can form the basis for reporting to consumers and the Government at a later date.

Audience

The target groups for this research were identified as:

1. The egg industry and AECL
2. Consumers (including retailers) via industry media releases
3. Government (research priorities, regulation requirements in the future).

3.2. Scope

Impact categories assessed

The impact categories addressed in this project (in line with recommendations from Harris & Narayanaswamy, 2009) are:

- GHG emissions – measured using the IPCC 2007 GWP factors on a 100 year time scale
- Energy Usage – using Cumulative Energy Demand (reported as lower heating value - LHV)
- Water Usage – using the water footprint definition, the ABS water use definition and the indicators proposed by Owens (2002). Further impact assessment in this area may be undertaken when methods are more clearly elaborated and agreed upon in the literature.

Functional Unit

The intent of this study was to investigate the primary production supply chain for egg production. The end point for this supply chain was deemed to be the distribution point prior to transport for retail. The functional unit is 1 kilogram of eggs ready for retail distribution (packaging excluded) in eastern Australia.

System Boundary

The system boundary extended from the cradle (breeding and hatchery) through to the end of the primary production supply chain (eggs graded and ready for packing and distribution to retail). The system was divided into foreground and background processes. The data for the foreground processes (identified by the dashed rectangle in Figure 2) was collected from Australian businesses.

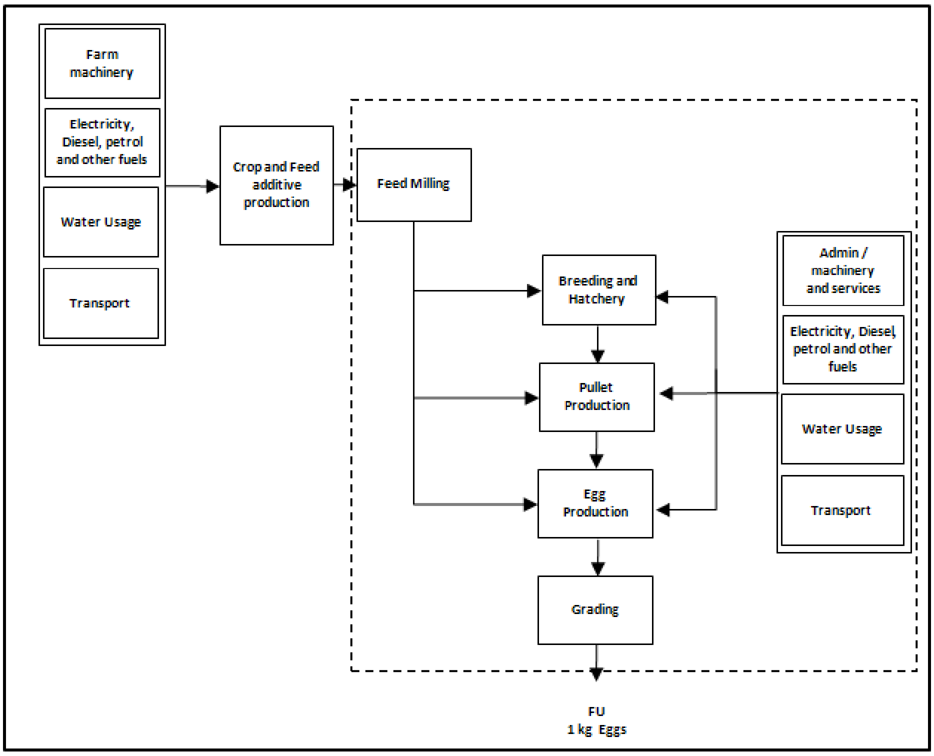

Figure 2. System boundary for the egg production system (foreground system within dashed rectangle)

Data Collection and Limitations

Foreground data were collected from farm records during site visits from late 2008 and mid 2010, covering an averaged 12 month production period, to account for seasonal effects and to balance production cycles. A 12-month production period was considered sufficient because of the uniform nature of production from modern egg production facilities.

Foreground data collection covered one breeder farm and hatchery, pullet rearing (all farms) and egg production (all farms). Data were collected from two grading facilities. Data collection covered all major processes relating to pullet and egg production, feed milling and egg grading. Farm administration, staff travel and infrastructure for the hen houses were included.

Manure production and GHG emission estimation was modelled based on bird production data, measured daily feed intake, feed formulations and measured manure characteristics.

Some minor veterinary and cleaning products used at the egg farm and grading floor were not included because of a lack of data. These products were used at low levels and represent a minor contribution. Additionally, some services (i.e. communications) were excluded because of difficulty in obtaining data.

Allocation

Within the foreground system, two allocation processes were required to handle the production of spent hens (hens slaughtered after the end of the egg production cycle) and manure (which contains valuable nutrients for crop production). Additionally, an allocation process was required in the background feed production system to handle co-production of protein meal and oil from canola and soybeans.

In the foreground system, the primary allocation method used was system expansion. Economic allocation was used as an alternative method to test the sensitivity of the model to allocation processes. Biological causality was not considered an appropriate method for two reasons:

i) it was difficult to partition manure fertiliser on this basis, and
ii) the value of spent hens would have been difficult to handle because they are sometimes treated as a very low value product and sometimes as a waste, despite being 7-8% of the output from the system by mass.

Spent hens

Spent hens are generally slaughtered for pet food or are disposed of on-farm via composting. The diversity of uses for spent hens made establishing a correct substitution product difficult. In the pet food market, meat may be sourced from by-product lines from many species (i.e. meat meal or offal, carcass off-cuts), but primary animal protein products are unlikely to be used because of cost. Consequently, plant protein may be the marginal substitute in the pet food market. Meat from spent hens was substituted on a 'protein equivalent' basis, assuming a protein yield (dry kg) of 19% from spent carcasses. Soybean meal (45% protein) was used as the marginal plant protein source.

Based on discussions with the farms involved in the study, the economic value of spent hens was deemed to be negligible and therefore no allocation was performed for the economic allocation scenario.

Manure

Manure from pullets and hens was substituted for synthetic fertiliser in the system expansion scenario for the main three nutrients of value: nitrogen, phosphorus and potassium. Nitrogen was substituted for urea, using a substitution ratio of 0.5 (i.e. manure nitrogen was assumed to replace 50% of urea nitrogen in a cropping system). Phosphorus was substituted for triple superphosphate using a substitution ratio of 0.6, and potassium was substituted for potassium chloride using a substation ratio of 0.8. These ratios were determined based on the expected efficacy of manure nutrients compared to synthetic fertilisers in a cropping system where manure is surface applied. The economic allocation process was based on 2010 retail fertiliser and egg prices.

Feed Grain

An allocation process was required to handle co-production of oil and protein meal in the background grain supply chain for canola and soy meal production. This was done using an economic allocation process because of the difficulty in determining substitution products for oil or protein.

Substitution processes were also applied to simplify the pullet and layer rations, and the methods used to achieve this are elaborated in section 4.1.

Critical Review

In accordance with ISO Standard 14040 (ISO 2006), a critical review was carried out for this project and review comments were addressed. This review was completed by Mr Tim Grant of Life Cycle Strategies Pty Ltd and is provided in Appendix 2, together with responses from the author and a final acknowledgement.

4. Life Cycle Inventory

4.1. Supply Chain Description

The supply chain included four egg production farms from eastern Australia. All farms were located in rural areas close to grain supply. A broad overview of climatic conditions for this region can be taken from the average temperature and rainfall for southern Queensland, which was the northern-most extent of the focus region (Table 6).

Table 6. Long-term average temperature and rainfall for southern Queensland

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Max. temp (°C)	30.8	29.9	28.7	25.9	22.3	19.1	18.5	20.3	23.8	26.7	28.5	30.4	25.4
Max temp. (°C)	17.8	17.6	15.6	11.9	8	4.1	2.7	3.6	7.2	11.3	14.3	16.6	10.9
Mean rainfall (mm)	77.2	83	45.3	32.7	40.4	29.6	30.5	24.9	30.8	56.9	79.7	92.2	624

Source: Bureau of Meteorology 2010.

To provide a representative result for the industry, data were collected from three separate enterprises in the region, all of which operated modern cage production systems with environmentally controlled housing and belt manure removal. The three farms collectively housed >1 M birds and all included pullet rearing operations. Egg grading facilities were also included in the foreground system. Additional data were collected from a breeding and hatchery facility, which supplied day-old chicks to the egg production farms.

In line with the goal and scope of the project, the system boundary incorporated the layer hen breeding system (breeding facility, hatchery, pullet rearing facility), feed production (grain growing, production of feed additives and feed milling), egg production and the grading and packing processes.

Additionally, a free range system was investigated for comparison. The free range system differed only at the egg production farm; upstream crop production, feed milling, pullet production and grading processes were identical to the caged production system.

Inventory data were aggregated from the three farms to ensure confidentiality for the data providers. Inventory data and assumptions are provided for the most important processes, including grain production (background process), pullet and egg production, energy use and transport, water use and estimation of manure emissions.

4.2. Feed Inputs

Feed inputs are the largest (and most expensive) input for egg production. Pullets and layer hens are fed on staged diets throughout their lives to optimise the nutritional efficiency of production, and feed formulations may also vary based on the cost of inputs throughout the year. For this reason, diets varied both within farms and between farms. Diet formulations and feed use data were also subject to confidentiality agreements with the farm owners.

To address these issues, average layer and pullet diets were determined for each farm over a 12 month period, and for the aggregated supply chain. Additional data regarding diet properties, such as dry matter percentage, energy and protein content, were collected to improve the accuracy of manure GHG emission modelling.

Developing Simplified Diets

The aggregated diet contained a large number of minor inputs and protein products. For protein products in particular, different products are substituted in the diet formulation based on the least cost. Because of the lack of LCI data for Australian protein products and minor feed additives, the aggregated diets were simplified using a substitution process to reduce the number of commodity inputs required. No substitution was required for the major cereal grains (sorghum and wheat), though several substitutions were required for protein meals.

Protein meals were substituted for either soybean meal or canola meal. Substitution was done on a 'kg of protein equivalent' basis following Wiedemann et al. (2010). The substitution process resulted in a 2.4% error in the mass of commodity inputs per tonne of feed (see Table 7) because of the lower protein levels in the two plant-based protein meals compared to some animal by-product meals.

A substitution process was also used to account for fats and oils, with all oils being substituted for canola oil. All minor feed additives were substituted for either lime or synthetic amino acids. Low-cost, mined inputs, such as salt, were substituted for lime, while high-cost inputs were substituted for synthetic amino acids using economic value to inform the substitution ratio. The simplified layer ration is shown in Table 7.

Table 7. Simplified ration for layer hens

Commodities (protein content in brackets)	kg / t
Sorghum (10%)	523
Wheat (13%)	167
Soybean meal (45%)	185
Canola meal (38.5%)	33
Canola oil	13
Limestone	90
Feed additives	13
Total	**1,024**

Feed Grains Input and Emission Data

Feed grains LCI data were collected from desktop assessments of Australian grain production processes, based on regional statistics for grain yields, literature sources and expert knowledge of production inputs. These data have been revised from a similar data set used in Wiedemann et al. (2010).

All cereal grain production was assumed to be no-till, as this is considered the marginal technology for grain production in Australia. The production, maintenance, repair and disposal of the agricultural vehicles were based on the EcoInvent process for tractor production. Because of a lack of process data, some minor pesticides were omitted. Changes in soil carbon for cropping soils were not considered in GHG assessment. Water use for grain production was considered separately and is discussed in section 4.3.

Nitrous oxide emissions in cropping arise from three sources: fertiliser application, indirect emissions associated with volatilisation losses during fertiliser application, and losses from nitrogen associated with crop residues. Emissions of nitrous oxide from all sources were based on the Australian tier 2 methodology (DCCEE 2010). These emission factors are reported in Table 8.

Table 8. Nitrous oxide emission factors for field crops

Source	NH_3-N loss factor	N_2O-N loss factor
N fertiliser application	0.1	0.003
Fertiliser volatilisation – resulting in indirect N_2O-N losses	n/a	0.01
Crop residue nitrogen	n/a	0.0125

Source: DCCEE (2010).

Soybean meal

The majority of soybean meal used in stockfeed in Australia is imported (Ansell & McGinn 2009), with 67% of imports originating in the USA. The unit process for soybean production was based on Australian data, with additional transportation to account for the use of imported soybean meal. Energy inputs for milling of soybeans and canola were based on Dalgaard et al. (2008), and impacts were allocated between meal and oil using economic allocation.

Other ingredients

Energy usage and GHG data for other feed ingredients were either based on literature or AustLCI unit processes. Data sources for relevant ingredients are presented in Table 9.

Table 9. Energy and GHG emissions for minor inputs to the layer and pullet rations

Ingredient	Energy (MJ/kg)	GHG (kg CO_2-e/kg)	Source
Synthetic amino acids: Lysine, Methionine, Threonine	86	3.6	Eriksson et al. (2005)
Limestone, at mine/AU U	0.061	0.007	AustLCI Unit Process

4.3. Pullet and Egg Production

Average supply chain production data are shown in Table 10.

Table 10. Pullet and egg production data

Pullet Production		
Age at housing	weeks	17
Mortality	% chicks placed	1.4
Feed ration	kg	6.1
Egg Production		
Age at end of production cycle	weeks	77
Cumulative mortality	%	3.5
Total egg mass per hen - day	kg	22.9
Feed consumption	g / bird / d	105
FCR	-	1.95

Production data could not be shown for free range production as these were confidential. However, for most egg production parameters, productivity was 5-15% lower than for the average of the environmentally controlled caged production systems.

4.4. Energy Usage and Transport

Average supply chain energy usage and transport data are presented in Table 11.

Table 11. Energy use and transport data for pullet and egg production

Pullet Production		Per Pullet	Uncertainty
Electricity	kWh	0.7	+/- 50%
LPG	MJ	1.9	+/- 100%
Staff transport	km	0.08	+/- 100%
Egg Production		kg eggs	
Electricity	kWh	0.13	+/- 30%
Petrol - farm	L	0.001	+/- 10%
Diesel - farm	L	0.001	+/- 15%
Staff transport	km	0.01	+/- 50%
Grading and administration		kg eggs	
Electricity - administration	kWh	0.0005	+/- 10%
Electricity - grading	kWh	0.0440	+/- 40%
LPG - grading floor	MJ	0.0909	+/- 20%
Petrol	L	0.0001	+/- 20%
Staff transport	km	0.0039	+/- 50%
Transport - commodities	t.km	0.0693	+/- 25%

4.5. Water Usage

The water use inventory was constructed from foreground water use data in the supply chain and from background data collected for upstream processes. Three water use categories were required to determine the water footprint of egg production (blue, green and grey water). Within the blue water category water use was further refined using the classifications and indicators proposed by Owens (2002) and the ABS classification.

Blue Water

Foreground water use

Blue water data were collected in the foreground system from farm records. At all farms water was sourced from groundwater aquifers. All farm water uses were classified as consumptive because water was evaporated from the system or was incorporated in the product. Almost all farm uses also contributed to the ABS water use category.

Table 12. Blue water use inventory data for egg production

Pullet Production		Water Source	Water Use Indicator	ABS water use	L / pullet reared	Uncertainty
Drinking		groundwater	Off-stream water consumption	yes	11.5	
Cooling		groundwater	Off-stream water consumption	yes	16.4	
RO Waste water*		groundwater	Off-stream water consumption	yes	9.2	
Total	L				37.1	+/- 60%
Egg Production					**L / kg eggs**	
Drinking	L	groundwater	Off-stream water consumption	yes	2.9	
Cooling	L	groundwater	Off-stream water consumption	yes	3.7	
Cleaning	L	groundwater	Off-stream water consumption	yes	0.0	
Surface Water Evaporation	L	surface water	Off-stream water consumption	no	0.1	
Waste water (RO)	L	groundwater	Off-stream water consumption	yes	2.3	
Total	L				9.1	+/- 70%
Grading						
Cleaning Water	L	groundwater	Off-stream water consumption	yes	0.8	+/- 40%

* Reverse osmosis brine

Water use for the free range egg production system was 6% lower than the caged farms because of the lower requirement for cooling water.

Background water use

Water use data for upstream processes is not well documented within the AustLCI and EcoInvent database, though all water uses are assumed to be consumptive and were assumed to be from extracted water sources (as per the ABS water use definition). Grain production was assumed to be from dryland cropping regions with no water use for irrigation. A notable exception to this was irrigation water use from imported soybean meal. Blue water use data for US soybean production was taken from Aldaya et al. (2010), who reported 263 m^3 water / tonne soybeans.

Green Water

Upstream water use

A detailed assessment of green water use in grain production was beyond the scope of this project, however because of the importance of this water source, an estimate was made using FAO 56 (REF) for the northern cropping region in Australia (see Table 13).

Results were reasonably similar to other published values for NSW wheat (i.e. Ridoutt & Poulton 2010) and Australian average wheat (i.e. Aldaya et al. 2010). For comparison, water footprint data previously reported by Hoekstra & Chapagain (2007) were adjusted to determine the green water contribution using the fraction of green:blue water for Australian wheat reported by Aldaya et al. (2010).

Green water use data for soybean meal imported from the USA were based on Aldaya et al. (2010).

Table 13. Green water use associated with Australian crop production

Crop	Units	This study	Based on Hoekstra & Chapagain (2007)	Ridoutt & Poulton (2010)	Aldaya et al. (2010)
Australian sorghum	m^3/ metric tonne	973	870*		
Australian wheat		1,129		1,197	1,209**
Australian barley		1,189	1,147		
Australian soybean		1,321	1,696*		
US soybean					1,295**

* Green water fraction of total water footprint disaggregated using a ratio of green water to virtual water of 0.73 for Australian wheat (after Aldaya et al. 2010).
** Data from Hoekstra & Chapagain (2007) and Aldaya et al. (2010) converted from US tons to metric tonnes.

Grey Water

Grey water use is a measure of the water required to dilute pollutants lost from the system. From agricultural systems, these losses are predominantly nutrients (nitrogen and phosphorus). Grey water use was assumed to be negligible and was not included in the water footprint for two reasons: i) grains in the northern cropping region are typically grown on heavy clay with low leaching rates, and ii) layer manure is handled according to strict environmental regulations to restrict leaching.

Grey water use was reported to contribute 4 - 8% of the water footprint of some grains by Ridoutt & Poulton (2010), though exact values were not reported and could not therefore be applied in the present study. Consequently, the water footprint in this study may be underestimated. A detailed assessment of grey water use for the grain production system was beyond the scope of this research.

4.6. Manure Greenhouse Gas Estimation

Greenhouse gases from manure management are an important source of emissions for many livestock systems. Manure emissions were estimated from farm data using two estimation methods. The emission estimation process first required modelling of the manure production parameters: volatile solids (VS) and nitrogen (N).

The primary method applied to estimate manure emissions was the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, using averaged input data from the supply chain. The IPCC is the global standard for estimating GHG emissions and is referenced as separate chapters:

- animal and manure management emissions (Dong et al. 2006); and
- soil emissions (De Klein et al. 2006).

These documents outline two ‘tiers’ of estimation methods. Tier 1 methods are simplistic emissions estimates provided from look-up tables in the manuals. The tier 2 methods include calculation formulas and emission factors for more refined emission estimation. The tier 2 methods allow for a ‘mix and match’ approach to be taken, where the methods or emission factors are interchanged with local data. In some instances, emission factors from the literature were applied where the IPCC manuals did not provide factors for the system under investigation. These are noted in the following sections.

The second method applied followed the *Australian National Greenhouse Accounts – National Inventory Report 2008* which represents Australia’s tier 2 methodology for calculating the national greenhouse gas inventory (NGGI). This is a streamlined, proscriptive national inventory method and does not include a detailed range of management systems or emission sources for poultry. This method has been applied directly as outlined by the manual without modification to approximate (on a farm-scale) the national inventory. This is referenced as the Department of Climate Change and Energy Efficiency (DCCEE 2010).

Manure Excretion Estimation

Feed Intake and Feed Properties

The first step in estimating methane and nitrous oxide emissions from manure management is to estimate manure excretion, and more specifically volatile solids (VS) and nitrogen (N) excretion. This requires information on daily feed intake and the properties of the diet. Intake and diet specification data were sourced from the case study farms. These data, along with the default DCCEE values are presented in Table 14.

Table 14. Average feed intake and crude protein levels for pullet and layer hens (as-fed)

Poultry Class	Layer hens		Pullets	
	Daily feed intake (g/hen/d)	Dietary Crude Protein	Daily feed intake (g/pullet/d)	Dietary Crude Protein
DCCEE default data [a]	122	18.3	122	18.3
Farm data	105	17.0	52	18.0

[a] DCCEE (2010) present assumptions on a dry matter basis. To convert these to As-Fed (i.e. accounting for moisture in the grain) the intake and crude protein values were multiplied by 1/0.9 (the average dry matter fraction of diets).

The IPCC (Dong et al. 2006) estimation method was followed using feed intake, energy and digestibility data from the farms to calculate VS. Excreted N was estimated using a mass balance equation based on feed intake and crude protein and N retention in the hens (liveweight and mortalities) and eggs. This resulted in an average N retention rate of 35%, which was mid-way between the 43% retention rate recommended by the DCCEE (2010) and the rate of 30% recommended by the IPCC (Dong et al. 2006). Based on the data presented in Table 14, the following excretion rates were generated (Table 15).

Table 15. Estimated N and VS excretion using the DCCEE or IPCC methods

Poultry Class	Layer hens		Pullets	
	Nitrogen excretion (kg/1000 hens/d)	VS excretion (kg/1000 hens/d)	Nitrogen excretion (kg/1000 pullets/d)	VS excretion (kg/1000 pullets/d)
DCCEE (2010) with default values	1.66	20.2	1.66	20.2
IPCC (Dong et al. 2006) with farm data	1.86	22.4	0.85	14.0

These values varied by around 5% because of variable protein levels in the diet and small variations in the level of N retention between farms. This was accounted for in the sensitivity analysis. Further elaboration of the methods and emission factors used for estimating manure emissions are provided in Appendix 1.

5. Results

5.1. Energy Usage

Cumulative energy demand for egg production from environmentally controlled caged production was 10.7 +/- 0.9 MJ / kg. The largest contributor to energy demand was feed production for layer hens and pullets. Energy use for feed production for layer and pullet ration was 3.9 and 3.9 MJ / kg ration produced respectively.

Farm electricity usage for housing (layers and pullets), feed milling and grading was the second largest contributor to total energy use. Most of the energy used at the farm level was used for hen housing. A system expansion process was used to account for the fertiliser value attributable to manure, which provided an energy offset of 10%.

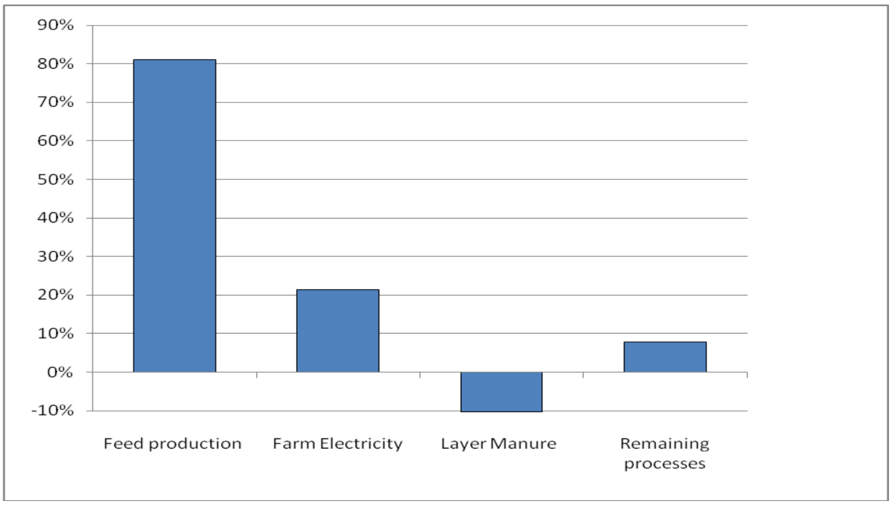

Figure 3. Contribution to cumulative energy demand for caged egg production

Cumulative energy demand for free range egg production was 13.1 +/- 1.1 MJ / kg eggs. The largest contributor to energy demand was feed production (76%), while farm electricity use (all uses) contributed 17%. The offset attributable to manure in the free range system was lower than the environmentally controlled housing system (6%) because of the deposition of manure outdoors (which was not given an offset value) and because of the higher ammonia volatilisation rates from the free range system, which resulted in less N in the litter available for land application.

5.2. Water Usage

Environmentally Controlled Housing

ABS and Consumptive Fresh Water Use

The ABS water use for egg production from environmentally controlled housing was 17.4 +/- 7.5 L / kg eggs. Of this, 11.4 litres of water use was from the foreground system (i.e. the breeder, pullet and layer farms and the grading facility only).

Consumptive fresh water use was similar for the foreground system, but had a significant additional water use component associated with imported soymeal from the US. This resulted in consumptive water use of 91.8 L / kg eggs, of which >80% was attributed to the imported soymeal. Contributions to consumptive water use are shown in Figure 4.

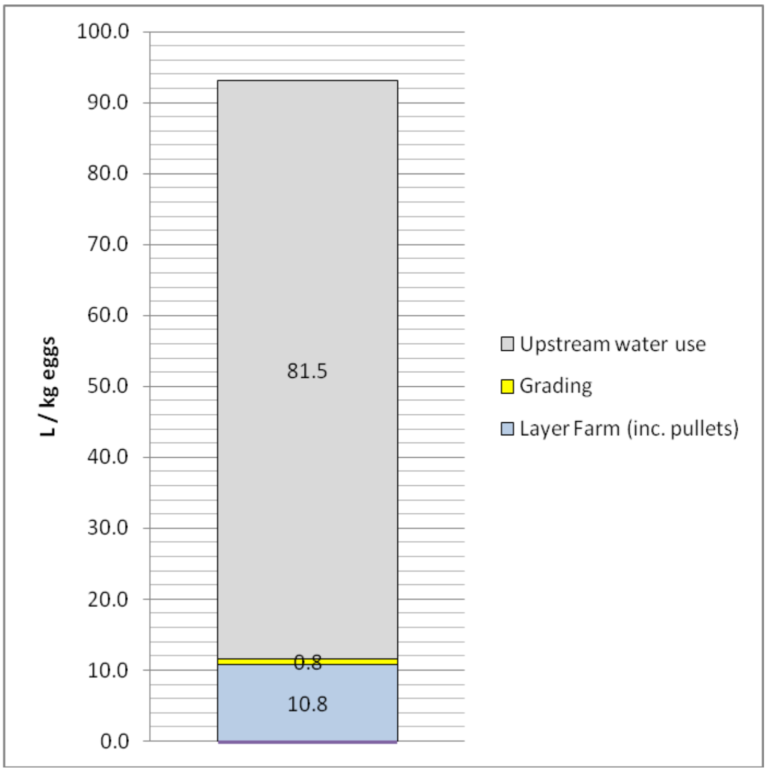

Figure 4. Consumptive fresh water use for egg production from environmentally controlled housing

Of the upstream consumptive fresh water use, 92% was contributed by imported soymeal.

Water Footprint

The water footprint (blue + green water) is shown in Figure 5. Blue water was taken from the consumptive fresh water use data.

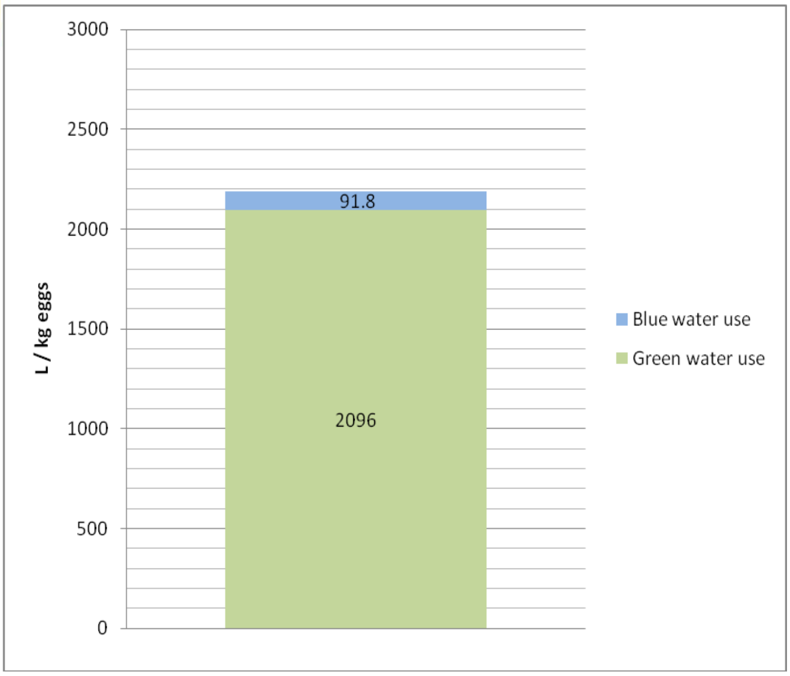

Figure 5. Water footprint for egg production from environmentally controlled housing

Free Range

ABS and Consumptive Fresh Water Use

ABS water use was 17.4 +/- 2.4 L / kg eggs. Water use for the foreground system amounted to 11.4 L / kg eggs. Consumptive fresh water use was considerably higher because of the additional water with imported soymeal (121.6 L / kg eggs). Contributions to consumptive fresh water use are shown in Figure 6.

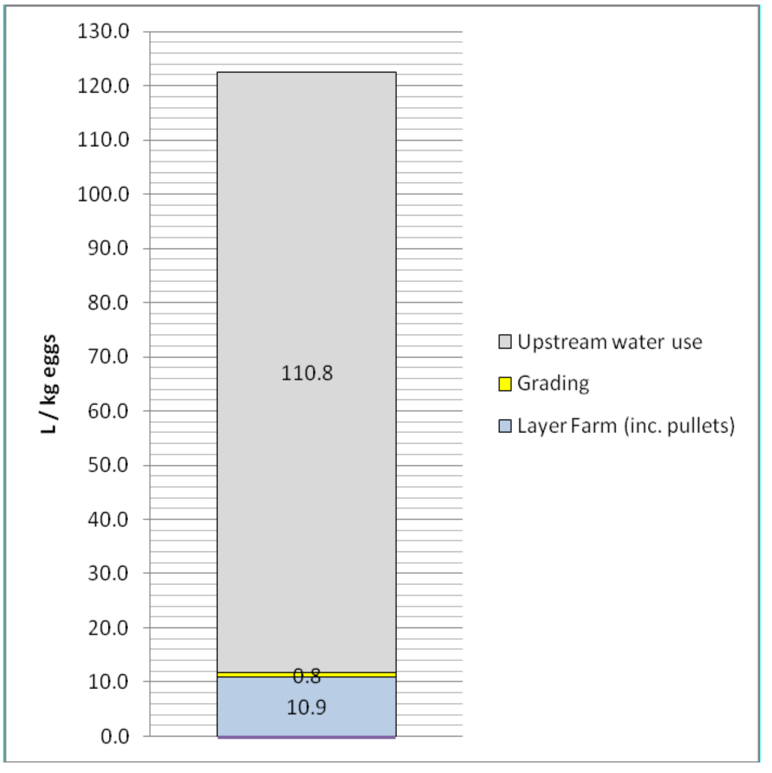

Figure 6. Consumptive fresh water use for egg production from a free range egg supply chain

Figure 6 shows the large contribution from upstream processes, of which the majority was from imported, irrigated soymeal from the USA (94% of the upstream water use).

Water Footprint

The water footprint was estimated as the sum of blue (consumptive fresh water use) and green water sources (grey water excluded). These results are shown in Figure 7.

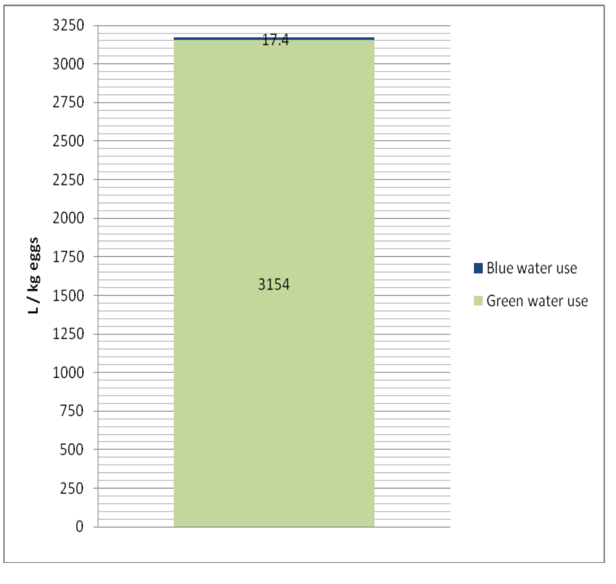

Figure 7. Water footprint for egg production from a free range egg supply chain

5.3. Greenhouse Gas Emissions

Environmentally Controlled Housing

Total GHG from egg production in environmentally controlled, caged housing was 1.3 +/- 0.2 kg CO2-e / kg eggs produced. Contributions to total GHG from individual gases (CO_2, N_2O and CH_4) are shown in Figure 8.

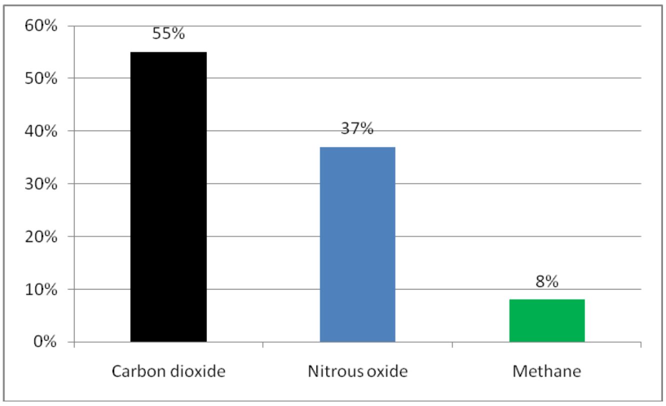

Figure 8. Contribution of individual gases to total GHG for egg production from environmentally controlled, caged production

Feed production is a major sub-component of the egg production supply chain. Total GHG for standardised rations were 0.28 and 0.29 kg CO2-e / kg ration (including transport and energy used for milling) for pullets and layer hens respectively. The main contributor to total GHG for both rations was CO_2 from fuel usage and fertiliser manufacture (68%). Nitrous oxide from crop production contributed 30% of total GHG.

Examining the main contributions to total GHG within the Australian supply chain identified three major sources: feed production, energy use and manure management (see Figure 9).

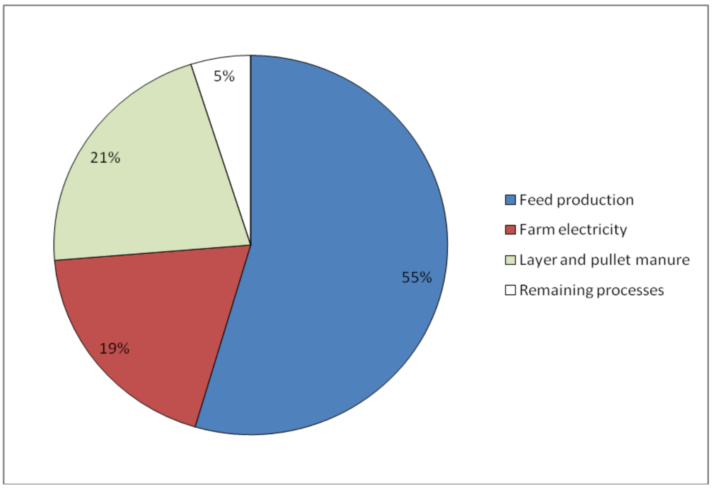

Figure 9. Total GHG contribution analysis for supply chain processes

The relatively high contribution from manure emissions was partly in response to the approach taken for aggregating emissions. In this study, manure emissions were accounted and reported separately rather than being considered as an input to feed production. System expansion was used to take into account the fertiliser value of manure. This approach allowed a clearer representation of emission sources and more accurately reflected the practices used in Australia, where manure is commonly sold from the egg farm to other users.

An alternative approach to investigating contributions was to look at the egg production and pullet production facilities separately. When this analysis was done, the main contributions are associated with feed production for layer hens (48%), energy use at the layer house, grading floor and feed mill (19%), pullet production (12%) and manure emissions from the layer hens (18%).

Free Range

Total GHG from free range egg production was 1.6 +/- 0.3 kg CO2-e / kg eggs. As with egg production from environmentally controlled housing, the largest contribution was from CO2 (see Figure 10).

The slightly higher contribution of N_2O was driven by higher manure emission factors for the free range system.

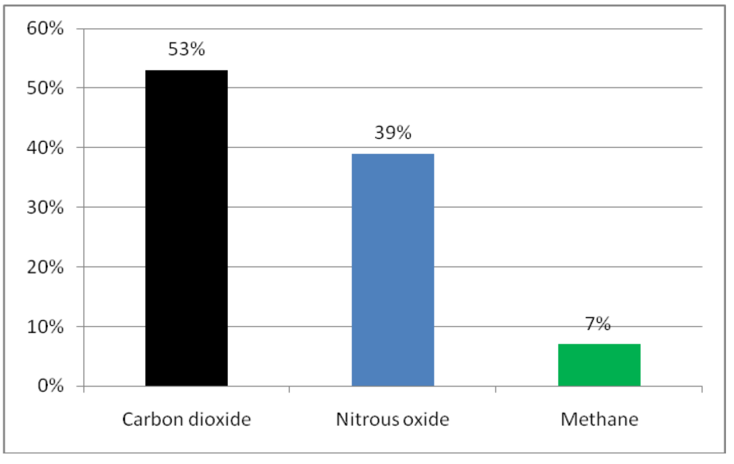

Figure 10. Contribution of individual gases to total GHG for free range egg production

6. Discussion

6.1. Uncertainty Analysis

The results in this study are subject to a certain degree of uncertainty, driven by natural variability in the system and assumptions made during the modelling process. Uncertainty was assessed using a Monte Carlo analysis in the LCA software program SimaPro™. Monte Carlo analysis is a means of handling cumulative uncertainty within the system. Rather than estimating a theoretical minimum and maximum (i.e. the cumulative lowest and cumulative highest values). the analysis estimates 1,000 scenarios based on the possible range of values for each parameter. These scenarios form an 'uncertainty range' for the system. This process was used to generate the 95% confidence interval for total GHG, energy use and water use.

Using this approach, a difficulty arises when comparing two different production systems that share some components, which was the case for the caged and free range systems in this study. Although the uncertainty analysis results appears to indicate that these production systems are not significantly different (at the 95% confidence level) a large degree of the uncertainty is shared between the two systems (i.e. uncertainty related to grain or pullet production, which are almost identical for both systems). This complicates the comparison. In order to compare these systems, the uncertainty of the difference between caged and free range production was investigated. This analysis was conducted by running a comparative test to measure the difference between the two systems. Results for this analysis are shown in section 6.5.

6.2. Energy and Water Usage

Energy Use

Energy use for the whole supply chain (cumulative energy use) was 18 - 40% lower for egg production from environmentally controlled housing than other studies presented in the literature (see Table 16).

Table 16. Energy use for Australian egg production compared with the literature

Reference	Production system	Energy Use (MJ/kg eggs)
This study	**Environmentally controlled housing - cage**	**10.7 +/- 0.9**
Williams et al. (2006)	cage	13.6
Sonesson et al. (2008)	cage	17.3
	cage	18.7
This study	**free range**	**13.1 +/- 1.1**
Dekker et al. (2008)	Free range organic	13.1
Williams et al. (2006)	Free range	15.4

Ration production was the main contributor to energy use. Within the feed grain production system, the main contributors were diesel fuel (for tractor operations and transport) and natural gas for urea production. Energy use associated with urea manufacture (taken from the AusLCI database with transport added to the northern cropping region) was 54.3 MJ / kg N. Associated emissions were 1.9 kg CO2-e / kg N, which is 40% lower than urea modelled from the EcoInvent database.

Energy use was lower than other Australian primary agricultural commodities (see Table 17).

Table 17. Energy use for three Australian animal production systems

Species	Primary Energy Use (MJ / kg product)	Reference
Egg production – this study	10.7 – 13.1	This study
Pork (carcass weight)	20.3 – 24.5[a]	Wiedemann et al. (2010)
Beef (carcass weight)	27.7 – 29.5	Peters et al. (2010)

[a] Results from this study are preliminary and may change when finalised.

Water Use

Water use was reported using a number of approaches, with the aim being to present results in the most clearly understandable way.

ABS water use is a reasonable estimate of competitive Australian water use, or the water used by the industry that is drawn from sources that could be utilised for other uses (industrial, domestic etc). Using this measure, egg production was found to use 17.5 L / kg. To place this in context, if 2 eggs were cooked by boiling in water (2 L), the production of the eggs would take only 45% more water than the cooking process. Consumptive fresh water use was considerably higher than ABS water use because of the inclusion of water used in the USA for irrigating soybean, which is subsequently imported to Australia.

Direct water use at the farm level was lower than other Australian primary agricultural commodities (see Table 18).

Table 18. Water use for three Australian animal production systems

Species	Water Use (L / kg product)	Reference
Egg production	11.4 – 11.6	This study
Pork (carcass weight)	41 – 49 [a]	Wiedemann et al. (2010)
Beef (carcass weight)	18 – 540	Peters et al. (2010b)

[a] Results from this study are preliminary and may change when further supply chains have been analysed.

This study presents the first disaggregated water footprint result for eggs produced in Australia, showing a total water footprint of 2,187-,2,543 L / kg eggs for environmentally controlled and free range systems respectively.

Free range production resulted in a 16% higher WF because of the higher grain use in this system. These estimates were higher than those reported by Hoekstra & Chapagain (2007) of 1,844 L / kg (units converted from original source). This was unexpected considering Hoekstra & Chapagain used a slightly higher water footprint estimate for Australian grain production, which contributed 99% of the water footprint of eggs in the present study.

The results show that 95-96% of the WF for egg production is green water (2,096-2,422 L / kg eggs), which is used directly in crop production. It has been noted by Ridoutt (Ridoutt & Pfister 2010) that green water use does not adversely impact aquatic environments, and clearly does not directly restrict water from other competitive uses such as industrial or domestic users.

6.3. Greenhouse Gas Emissions

The total GHG emissions from Australian egg production were lower than estimates reported in the literature for studies completed elsewhere in the world (see Table 19). Comparison of results between LCA studies should be done with caution because of the different assumptions used from one study to the next; however, there are some clear drivers for lower GHG from Australian egg production systems compared with the literature (see section 6.5).

Table 19. Comparison of total GHG from Australian and international egg production studies

Reference	Production system	GHG (kg CO_2-e / kg eggs)
Caged Production		
This study	**environmentally controlled housing – cage**	**1.3 +/- 0.2**
Cederberg et al. (2009)	national average - predominantly cage	1.4
Sonesson et al. (2008)	cage (included retail and packaging)	1.6 - 1.8
Verge et al. (2009)	cage	2.5
Mollenhorst et al. (2006)	cage	3.9
Williams et al. (2006)	cage	5.25
Free Range Production		
This study	**free range**	**1.6 +/- 0.3**
Dekker et al. (2008)	free range, organic	4
Mollenhorst et al. (2006)	free range	4.6
Williams et al. (2006)	free range	6.18

It is difficult to compare eggs with other animal systems because of differences in the primary product and functional units selected for the studies. Comparisons must take into account physical and quality factors that influence the product. This being said, a general indication of the trend between products can be seen from the reported GHG from primary products for pork and beef (see Table 20).

It is noted that research is on-going for each species and results may change as more comprehensive results become available. In a more detailed analysis, egg production was shown to compare favourably to meat products on a 'per kilogram of protein' basis (de Vries & de Boer 2010).

Table 20. Total GHG for three Australian animal production systems

Species	Total GHG (kg CO_2-e kg product)	Reference
Egg production	1.3 - 1.6	This study
Pork (carcass weight)	3.1 – 5.5 [a]	Wiedemann et al. (2010)
Beef (carcass weight)	9.8 – 11.5	Peters et al. (2010a)

[a] Results from these studies are preliminary and may change when finalised.
It should be noted that the functional units are not directly comparable for these studies.

GHG Mitigation Options

Mitigation options for the egg industry must focus on areas where the largest gains can be made in a cost effective way, without compromising productivity. One of the most favourable approaches to reduce total GHG is to improve FCR. Provided productivity can be maintained, this will also lower production costs. However, reductions in FCR may not result in large improvements because of the high degree of efficiency currently achieved by the industry and the slow rate of improvement in FCR over time. Because nitrous oxide in the manure system is a major contributor to total GHG, the use of rations with lower nitrogen levels will also lead to lower emissions.

Farm energy use is perhaps the most beneficial target for mitigation strategies because of the cost benefit opportunities associated with lowering energy use. Mitigation of energy emissions can be achieved using two different approaches:

i. reducing energy use; or
ii. the use of renewable energy.

Reducing energy use will reduce input costs and improve efficiency, provided production levels can be maintained. This is the most favourable option for the industry. Investigation of renewable energy use is also an opportunity for the industry, either through production of energy from manure or through purchase of other renewable energy sources.

The third option for reductions in GHG is through improved management of manure to reduce nitrous oxide and methane emissions. It should be noted that the manure emission factors used in this study were international defaults and are unlikely to accurately reflect Australian conditions (particularly for emissions associated with manure application). Australian research is required to test these emission factors. Considering similar research for nitrous oxide from grains (discussed earlier) showed Australian emissions were considerably lower than international defaults, it is possible that manure GHG is lower in reality than estimated here.

Noting the lack of research with respect to manure emissions, there are also strategies that will reduce emissions from this source in a cost effective way. The most attractive option is to process manure to generate energy from volatile solids (VS). Several potential waste-to-energy technologies exist, including anaerobic digestion (AD), pyrolysis and combustion. It should be noted, however, that most research on the feasibility of these technologies for poultry systems have focussed on meat chicken production, where manure is mixed with a dry, high energy litter product (usually wood based). In contrast, layer hens produce high moisture (50 - 70%) manure that also has high levels of ash and nitrogen. These properties limit energy recovery options for the product. Importantly, studies that investigate the use of litter products are of little value when assessing the options for energy recovery from layer manure. Perhaps the most promising option available is solid phase, leach bed anaerobic digestion, provided soluble nitrogen can be effectively managed. Energy recovery from manure may also enable drying and processing of manure, increasing the value and efficiency of nutrient reuse.

Comparison of the IPCC and DCCEE Estimation Methods for Manure Emissions

An additional scenario was run to investigate the differences between the IPCC methodology and the DCCEE methodology for estimating manure emissions. In this scenario, the DCCEE (2010) method resulted in a slight increase of 6 – 7% in total GHG. The DCCEE (2010) methodology was followed straight from the manual without any alterations. Key assumptions and emission factors are provided in Appendix 1.

The DCCEE provided default values for feed inputs and feed properties in order to generate excretion values for VS and N. Feed consumption was 5% higher than the average for farms in the study. Despite this, excreted VS from the actual diets were lower than estimated because the predicted digestibility in the DCCEE manual was higher than the actual diets fed. Excreted N estimates were lower than the estimate based on actual feed and production data. The DCCEE method overestimated feed intake and underestimated dietary crude protein compared to the farm average. Additionally, the DCCEE recommended a fixed level of N retention (43%) which was higher than estimated by using a mass balance approach (35%) with the actual production data.

The DCCEE estimated lower methane emissions overall (28% lower than estimated using the IPCC) as the methane potential (B_o) and methane conversion factors (MCF) were both lower than the IPCC. Consequently, the contribution from methane to overall GHG dropped from 9% (IPCC) to 6%. However, emissions from pullet rearing and some nitrous oxide emissions were higher, increasing the overall emissions estimated.

6.4. Comparison of Caged and Free Range Production

Comparing caged and free range production shows the relative energy efficiency of production from environmentally controlled, caged housing (18% less energy per kg eggs). This result was driven by the higher FCR for free range birds compared to caged production, leading to higher upstream energy use. Blue water and ABS water use was similar between the two systems, though green water use was 16% higher for the free range system because of the higher FCR.

Likewise, total GHG was 23% higher from the free range production system than the caged system. The analysis of uncertainty between these two systems showed that caged production had lower emissions in 97% of the scenarios, which indicates a significant difference between the two production systems despite the overlapping confidence intervals. As with energy and water, the higher total GHG for the free range system was primarily in response to higher grain use.

Estimated manure emissions were also slightly higher for the free range system because of the higher emission factors recommended by the IPCC for manure deposited directly to soil. These increases offset the lower electricity use at the farm level for free range production.

6.5. Sensitivity Analysis

The total environmental impacts from egg production were driven by a comparatively small number of processes and inputs to the system. From the contribution analysis it was clear that the main contributors to energy and total GHG were feed production and farm electricity use. Additionally, manure management was also a large contributor to total GHG.

Feed Use and Upstream Feed Production

The single largest contributor to total GHG was the use and production of layer and pullet feed. Hence the system was highly sensitive to the amount of feed used per kilogram of eggs produced (feed conversion ratio – FCR) and the unit processes for feed grains used in the rations.

Feed conversion ratio averaged 1.95 kg feed / kg eggs for caged egg production in the present study. This was lower than most studies reported in the literature (see Table 5), but was comparable to Cederberg et al. (2009) and Sonesson et al. (2008) and is in line with industry targets.

To investigate the sensitivity of the system to FCR, an analysis was run by altering the FCR, assuming no other changes. The effects of changes in FCR are presented in Table 21.

Table 21. Sensitivity of total GHG to changes in layer hen FCR

FCR	Change in total GHG
1.9	-1.7%
1.95	0 %
2.0	+0.8%
2.4	+10.9%

Feed conversion ratio is one of the most important production parameters for the industry, and is closely monitored and managed. Hence it does not vary greatly across the industry.

To test the sensitivity of the model to the upstream grain production processes, a brief literature review was done focussing on the main cereal and protein feed inputs (see Table 22).

Table 22. Comparison of total GHG for major feed grain inputs in the literature

Grain	Country	Key System Parameters	GHG (CO_2-e / t)	Reference
Wheat	Australia	Zero-till, low yield, low N input, nitrous oxide emission factor of 0.3%	221	Present study
Wheat	Australia	Low intensity, low yield, 22% of total GHG from N_2O (using lower Australian emission factor of 0.3%)	304	Biswas et al. (2008)
Wheat	UK	High intensity, high yield, 70% of total GHG from N_2O	700	Williams et al. (2010)
Wheat (protein corrected to 13%)	Switzerland	High intensity production, 46% of total GHG from N_2O	371	Charles et al. (2006)
Barley	Australia	Low intensity and yield, 48% of total GHG from N_2O (using outdated 1% emission factor)	437	Narayanaswamy et al. (2004)
Corn	USA	High yield, mixed tillage and variable N_2O depending on region investigated, approx. 50% of total GHG from N_2O	254 - 825	Kim et al. (2009)
Sorghum	Australia	Zero-till, low yield, low N input, nitrous oxide emission factor of 0.3%	176	Present study
Soybean meal	Australia market	Market mix – 80% imported from the USA, 20% grown in Australia in minimum-till, low-yield systems	401	Present study

The main cereal and protein grain processes used in this study have been modified from processes published in Wiedemann et al. (2010). There are three clear reasons why no-till grain production systems in the northern grains region of eastern Australia are expected to generate lower levels of GHG per tonne of grain produced compared to European systems. These are:

i. the nitrous oxide emission factor for Australia is considerably lower than the default value for Europe (the Australian factor is 0.3% - DCCEE (2010) compared to 1% in the IPCC – de Klein et al. 2006);
ii. the farm energy intensity (MJ/t) of Australian grain production tends to be lower than European production systems; and
iii. fertiliser use is generally lower than European systems.

Fertiliser use in Australia's northern grain production region is relatively low (at or below nutrient replacement level for nitrogen and phosphorus – NLWRA 2001). It should be noted that this is not sustainable in the long-term, raising other sustainability concerns for the feed grains industry and industries that rely on it.

Considering the importance of these feed grain systems, further research is required to identify the range of likely emissions arising from these systems to reduce the uncertainty of the analysis. Differences in feed use (related to both FCR and upstream feed grain production) were the largest factor contributing to differences between the GHG results from this study compared to others in the literature (see Table 23).

Table 23. Comparison of feed contribution to total GHG for three egg production studies

	Mollenhorst et al. (2006)	Sonesson et al. (2008)	This study
Total GHG (kg CO_2-e / kg eggs)	3.9 (cage)	1.7 (cage – av. of two farms)	1.3 (cage)
GHG contribution from feed (kg CO_2-e / kg eggs)	3.1 (80%)	1.2 (69% av. of two farms)	0.7 (55%)
Contribution from all other sources (kg CO_2-e / kg eggs)	0.8	0.5 (includes packaging and retail)	0.6

Modelling of Manure Emissions

Manure emissions contributed 21% of overall GHG for the caged production system. There were a number of sensitive assumptions within the manure emission modelling process. Nitrous oxide emissions from the application of manure contributed slightly over 10% of total GHG, which was largely driven by the relatively high nitrous oxide emission factor recommended for land application of manure (1% of applied N). This factor is based on research from Europe rather than Australian conditions. Considering the low emission factor recommended by the DCCEE (2010) for inorganic fertiliser application (0.3%), the manure emission factor may be an overestimate.

Farm Energy

Farm electricity use contributed 19% to GHG and 16% to overall energy use. Electricity use varied between the farms, and considering the small sample size this may be an important area of variability throughout the industry.

Allocation Method

The sensitivity of the model to allocation method was tested to compare the preferred method (system expansion) to an economic allocation process. Economic allocation resulted in 3% higher GHG for both caged and free range production. Similarly, CED was 6% and 9% higher for the caged and free range systems respectively. System expansion was used as the preferred approach following the ISO recommendations.

7. Conclusions and Recommendations

Australian egg production is a highly efficient form of protein production with respect to the environmental impacts and resource use issues addressed in this study. Results from a modern Australian production system (environmentally controlled, caged birds) indicate that total GHG from Australian egg production (1.3 +/- 0.2 kg CO2-e / kg eggs) was similar to one recent study (Cederberg et al. 2009), but was considerably more efficient than frequently quoted studies such as Williams et al. (2006). Similarly, free range production in this supply chain was highly efficient (1.6 +/- 0.3 kg CO2-e / kg) when compared with the literature.

Cumulative energy demand for caged production (10.7 +/- 0.9 MJ / kg eggs) was lower than studies previously reported in the literature. Cumulative energy demand for free range egg production was slightly higher than for caged production (13.1 +/- 1.1 MJ / kg eggs), but was similar to other studies reported in the literature.

The relative environmental efficiency of egg production in this study arose from the high performance of modern Australian egg production coupled with the low input nature of Australian grain production. Australian grain is produced in conditions that do not favour nitrous oxide emissions, which is reflected in the lower emission factor recommended for use in the Australian inventory (DCCEE 2010). These result in low GHG and energy use for Australian eggs both in the caged and free range systems.

Few studies were found in the literature that investigated water usage. Water use was calculated using three approaches. Of these, ABS water use (17.4-17.5 L / kg eggs) is most easily comparable and understandable figure, being a reasonable estimate of the industries' competitive water use. Further impact assessment for water use was not carried out.

The study identified green water as the major contributor (95-96%) to the total WF for Australian eggs. Considering this, the WF for eggs is clearly not a good measure of the egg industries' impact on competitive water uses in Australia, or of the environmental impacts of water use. The ABS or blue water use volumes are more comparable to other agricultural or urban water uses.

The contribution analysis showed that feed grain production and use was the largest impact source, followed by on-farm water and energy use, and manure management (for GHG only).

Consequently, mitigation strategies and efficiency measures that reduce feed use would be highly beneficial to the industry. However, considering the high degree of feed efficiency achieved to date, substantial further gains are expected to be more difficult to achieve.

Reducing farm electricity use is another attractive mitigation strategy for the industry that will lead to lower energy use, lower GHG and lower costs provided production levels can be maintained.

Emissions from manure management were estimated using the default values provided by the IPCC (Dong et al. 2006). These were found to allow a greater degree of flexibility than the Australian tier 2 methodology (DCCEE 2010). Results from the

DCCEE scenario were similar to results based on the IPCC, despite the omissions and likely errors in the DCCEE methodology. Further research into manure management and emission factors would be warranted to improve estimation methods.

Based on the results of this study, the following recommendations are provided:

1. Further investigation of Australian feed grain systems is required to improve the quality of LCI data for the egg production system. Because of the large contribution of ration production to the egg supply chain for GHG, energy and water use, this should be seen as a high priority for the industry in collaboration with other animal industries.

2. A broader spectrum of egg producers from other production regions are required to produce results that could be considered representative of the whole Australian industry.

3. Mass balance research is required to quantify mass flows, excretion and emission rates from modern cage and free range production facilities. The highest priorities in this area are:
    - Updated emission factors from manure application
    - Updated ammonia emission factors for layer sheds
    - Updated nitrous oxide emissions from layer sheds
    - Manure reuse and mass flow research to update and improve the flexibility of the DCCEE methodology, particularly for free range systems
    - Updated ammonia, nitrous oxide and methane emissions from stockpiles.

4. Collection of energy and water benchmarking data across a greater cross section of the industry is required. The data will provide a robust basis for targeting industry improvement and could be integrated into future LCA studies.

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Appendix 1

Manure Management from Environmentally Controlled, Caged Egg Production

Manure Handling Practices

In the present study, all layer houses were fitted with manure belts, with manure being removed twice per week. Removed manure had a moisture content of 50-67% (from analyses taken at each farm). Manure samples from sheds fitted with manure belts tend to have higher levels of residual carbon and nitrogen than high rise sheds, suggesting that losses are lower (Wiedemann et al. 2008).

Manure emissions are accelerated by high moisture, wetting/drying and anaerobic conditions. Emission factors from manure management are also higher for longer residence times (Dong et al. 2006). Considering the short residence time and likelihood of predominantly aerobic conditions on the manure belts, emissions are not expected to arise from the pullet or hen house.

After manure is removed from the shed it is stored or transported to the field for application. All farms aimed to minimise manure storage time on-farm. However, in some months of the year demand for manure is low and storage for periods of 1-3 months may occur. It was estimated that 30% of the manure produced in the year is stored for a period of 1-3 months (stored manure), and the remaining manure was stored for less than 1 month (rapid spreading).

Emission Sources

Dong et al. (2006) provide emission factors developed for older style high rise sheds only. Considering the manure residence time in these sheds may be 60 weeks compared to 3-4 days for the new shed systems, these factors were deemed to be inappropriate and were not applied. A small loss of ammonia from the sheds was estimated based on literature sources. Emission factors for manure storage have been applied where manure residence time in storage exceeded 1 month.

The DCCEE method does not allow for specification between housing and storage emissions, hence the housing emission factors were applied for the DCCEE scenario.

Generalised emission formulas for both the IPCC and DCCEE (2010) are provided in the following sections for reference.

Manure Methane

The methane emission formula is as follows:

$M_{ij} = VS_{ij} \times B_o \times MCF \times p$

Where:

VS_{ij}	=	volatile solids excretion (Table 15).
B_o	=	methane potential factor (m^3 CH_4/kg VS).
MCF	=	Integrated methane conversion factor (%).
p	=	density of methane (0.662 kg/m^3).

The IPCC (Dong et al. 2006) and the DCCEE (2010) provide different values for B_o and MCF for layer hens. These are summarised in Table 24.

Table 24. Methane potential and conversion factors from the DCCEE and IPCC as used within this study

	IPCC		DCCEE	
B_o	MCF (stored manure)	MCF (rapid spreading)	B_o	MCF
0.39	4% [b]	1.0% [c]	0.32	2%

[a] IPCC (Dong et al. 2006)
[b] This factor is recommended for 'solid storage in temperate climate' (15-25° C).
[c] This factor is recommended for daily spreading of manure.

Manure Nitrous Oxide

Direct nitrous oxide emissions from manure management were calculated using the general formula reproduced below.

$E_{MMS} = NE \times MMS \times EF_{(MMS)} \times C_g$

Where:

NE = Nitrogen Excretion – (see Table 15).
MMS = The fraction of birds that are managed in a specified manure management system.
$EF_{(MMS)}$ = The emission factor for the relevant manure management system.
C_g = The factor to convert mass of N_2O-N to molecular mass (44/28).

The factors for different manure management systems are reported in Table 25.

Table 25. Manure management systems and emission factors for nitrous oxide from the DCCEE and IPCC as used within this study

MMS	IPCC [a] emission factor for nitrous oxide	DCCEE emission factor for nitrous oxide
Poultry manure (cage housing)	0 [b]	0.005
Poultry manure (stored manure)	0.005 [c]	n/a
Poultry manure (rapid spreading)	0 [d]	n/a

[a] IPCC (Dong et al. 2006)
[b] For poultry manure without litter (cage systems) all emissions were attributed to the manure storage or spreading stage
[c] Solid storage
[d] Emissions considered under land application

Manure Ammonia Emissions

Ammonia emissions were determined as part of the mass balance and to estimate indirect emissions of nitrous oxide via ammonia deposition (as per the DCCEE and IPCC methods).

As with methane and nitrous oxide, the short manure residence time restricts ammonia emissions within the shed. Ammonia emissions from houses fitted with manure belts may be 3-10 times lower than those recommended by the IPCC (see FSA Consulting 2007, Groot Koerkamp et al. 1998). Hence, the emission factor was revised based on these literature sources. The factors used are summarised in Table 26.

Table 26. Manure management systems and emission factors for ammonia from the DCCEE, IPCC and literature sources as used within this study

MMS	IPCC / literature emission factor for ammonia	DCCEE emission factor for ammonia
Poultry manure (cage housing)	0.05 [a]	0.55
Poultry manure (stored manure)	0.12 [b]	n/a
Poultry manure (rapid spreading)	0.0 [c]	n/a

[a] Factor from the Australian National Pollutant Inventory (NPI) poultry ammonia emissions review has been applied (FSA Consulting 2007). [b] Solid storage for 'other' manure (Dong et al. 2006). [c] Emissions considered under land application.

Land Application Emissions from Manure

Manure N applied to fields is a source of nitrous oxide emissions. Nitrogen applied to fields was calculated as:

$N_{applic} = N_{excreted} - N_{losses}$ (N_2O-N and NH_3-N from sheds and storage).

The DCCEE and IPCC provide different emission factors for ammonia arising from manure application. These are summarised in Table 27.

Table 27. Manure application emission factors from the DCCEE and IPCC as used within this study

Emission	IPCC [a] emission factors	DCCEE emission factors
Nitrous oxide	0.01	0.01
Ammonia	0.2	0.0

[a] IPCC (De Klein et al. 2006)

Indirect Nitrous Oxide Emissions

Indirect emissions of nitrous oxide occur as the result of ammonia volatilisation from the egg production system and from ammonia volatilisation during manure application. This occurs because ammonia is deposited onto land where it contributes to a pool of soil nitrogen, some of which is re-emitted as nitrous oxide. These indirect emissions are attributed to the facility responsible for the ammonia emissions.

Ammonia emission factors and total ammonia losses (as a percentage of excreted N) are shown in Table 28.

Table 28. Aggregated ammonia emissions from egg production systems

Emission source	IPCC and literature emission factor for ammonia	DCCEE emission factor for ammonia
Poultry shed	0.05 [a]	0.55
Manure storage	0.12 [b]	0.0
Land application	0.20 [b]	0.0
Total NH_3-N as a proportion of excreted N	**0.27**	**0.55**

[a] Australian NPI review (FSA Consulting 2007) [b] IPCC (De Klein et al. 2006, Dong et al. 2006)

Of the nitrogen lost as ammonia (NH_3-N), the DCCEE and IPCC apply an emission factor of 0.01 (1%) to calculate indirect nitrous oxide emissions. However, because of the differences in estimated ammonia emissions from these sources, overall emission rates differ between the two methods.

Indirect nitrous oxide emissions may also arise from nitrogen that is leached or lost from runoff, depending on the climatic conditions that drive these processes. In this study, leaching and runoff have not been considered an emission source because of the very low levels of leaching and runoff that occur in the egg production region. This was done in accordance with the Australian tier 2 methodology DCCEE (2010).

Manure Management Emissions from Free Range Systems

Manure Handling Practices

Free range poultry systems utilise a different manure management system and require a different suite of emission factors to reflect these differences. In the free range system, a proportion of manure is deposited indoors (on litter or slats) while a proportion is deposited in the outdoor range. Manure deposited indoors is kept in the sheds for the full length of the production cycle (about 60 weeks) prior to removal.

Emissions from manure deposited indoors or outdoors is subject to different environmental conditions, leading to different emissions. Consequently, different emission factors are appropriate for manure deposited in these different areas. Determining the proportion of manure deposited indoors or outdoors is important for accurately determining the GHG emissions from manure, though little research is available on this. Hirt et al. (2000) reported that 19.5% of birds in larger flocks (3000 birds) used the outdoor range during a summer observation period. By using the proportion of time spent outdoors as a proxy for manure deposition, we estimated that 20% of manure from the free range system was deposited in the outdoor range and 80% was deposited indoors.

Emission Sources

Emission factors for methane, nitrous oxide and ammonia are presented in Table 29 for manure deposited indoors and outdoors.

Table 29. Manure management systems and emission factors for free range poultry from the DCCEE and IPCC as used within this study

Emission	IPCC emission factors		DCCEE emission factors
Manure deposition	Indoor (on litter)	Outdoor (on pasture)	Not differentiated
Methane	1.5%	2%	2%
Nitrous oxide	0.001	0.02 [b]	0.02
Ammonia	0.4	0.2	0.4

[a] Emission factor from IPCC (Dong et al. 2006)
[b] Emission factor from IPCC (De Klein et al. 2006)

Appendix 2

Critical Review and Author Responses

Report Section	Review – Tim Grant (Life Cycle Strategies)	Author response
Project Goal	The goal of the study is sufficiently defined. It is not identified how the public consumer information will be used, and this can be important in terms of how the LCA is presented and calculated. For example, the carbon trust label requires different carbon accounting rules to conventional LCA.	Addressed. Goal clarified to highlight that the project is to provide indicative information to the general public, not specific information for labelling.
Functional Unit	Some geographical parameters should be considered in addition either based on the supply (from the Queensland and NSW suppliers) or based on the market: 'for the East Australian Market'. If the sampled facilities are being used as an estimate of the Australian market, then this should be stated.	Addressed. A descriptor has been added to identify that the egg supply chain is based in eastern Australia. Modelling of the distribution network was beyond the scope of the project.
System boundary	The system boundary is well defined and appears to comprise all the relevant components, including all feed and infrastructure.	No comment required.
Indicators	The international standards advise that the LCA should include a broad selection of relevant indicators in line with the goal and scope of the study. The restriction of the study to greenhouse gases (GHG), cumulative energy demand and water is in line with the brief. Other relevant indicators which could be considered are land use, due to crop and feed requirements, and eutrophication potentially from site run-off and cropping systems.	No comment required.
Allocation	There is much debate and controversy about recycling credits and allocation, and they can be important in agricultural systems where many components are co-produced. There are multiple approaches used in the study. System expansion is used to deal with manure use as fertiliser, and economic allocation is used for co-production of high protein meal from canola and soybean. Some justification for this decision (not to follow the ISO hierarchy first options) should be provided. If it was made for the sake of simplicity and justified by the low contribution, then this should be stated in the goal and scope and not just in the final analysis of the results. These should also be tested in a sensitivity analysis to determine if the choice of allocation method is affecting the results of the study.	Addressed. The project has been revised to apply two approaches (system expansion and economic allocation for the foreground system) to address this issue and identify the sensitivity of different allocation approaches. Regarding allocation processes in the upstream protein meal supply chain, the choice to use economic allocation is based on the difficulty in applying system expansion where almost all protein meals are co-produced, making system expansion difficult. This has been further clarified in the report.

		Addressed. Allocation method has been included in the sensitivity analysis.
Cut-off criteria	No cut-off criteria have been included. If each exclusion is handled on a case-by-case basis, and includes an evaluation of the difficulty in getting the data and their potential impact on the system, this could be stated in the goal and scope.	Addressed. Handling of exclusions has been clarified in the report. These were handled on a case-by-case basis. The only exclusions were veterinary products and minor chemicals where data were difficult to obtain from the farms.
Inventory	It is not clear why the feed substitution has been done on a mass basis, when the functional basis of the feed is protein.	Substitutions were done on a "kg of protein equivalent" basis, this has been further clarified in the report.
Data quality assessment	There is no formal data quality assessment provided in the report. This can be done in a qualitative way with scoring and/or commentary on the data quality, or a quantitative way using uncertainty assessment	Addressed. Formal sensitivity and uncertainty section added to the discussion section.

Appendix 3

Life Cycle Strategies

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Final Review Statement

1st December 2010

Environmental Assessment of an Egg Production Supply Chain Using Life Cycle Assessment

To whom it may concern
The Environmental Assessment of an Egg Production Supply Chain Using Life Cycle Assessment was reviewed in November 2010 with comments being provided back to FSA Consulting which were addressed in the final report dated December 2010.

After considering the additions and responses made in this report this study now provides a rigorous assessment of the greenhouse gas emission, energy use and water use for egg production in eastern Australia. The study is compliant with the ISO 14044 standard within the defined goals for the study and this is verified through the comparison of the results with other international studies.

Regards

Tim Grant
Director, Life Cycle Strategies Pty Ltd