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Environmental impacts of the Australian poultry industry: 2. Egg production

M. A. Copley[A,*], S. G. Wiedemann[A] and E. J. McGahan[A]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
M. A. Copley
Integrity Ag and Environment, 10 Neil Street, Toowoomba, Qld 4350, Australia
Email: maryfrances.copley@integrityag.net.au

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ABSTRACT

Context. Eggs, a dietary staple, are a low environmental-impact animal protein, although no quantified analysis has been published for the Australian egg industry. **Aims.** This study determined baseline greenhouse-gas (GHG) emissions, fossil energy use, freshwater consumption, water stress, and land-occupation impacts for the Australian egg for 2020 and identified hotspots. **Methods.** To understand the environmental credentials of the industry, an attributional life-cycle assessment was conducted using primary data collected from all major Australian production regions. Impacts were reported per kilogram of table eggs and per kilogram of shell- and protein-corrected eggs for cage (C), cage-free (CF) and free-range (FR) production. Monte Carlo analysis was used to assess uncertainty, and results are presented using the means and standard deviations. **Key results.** Statistically significant ($P < 0.05$) differences among all systems were found for GHG and land occupation, and between cage and non-cage systems for fossil energy use. Impacts were 1.2 ± 0.04 kg carbon dioxide equivalent (CO_2-e), 10.7 ± 0.2 MJ, 177.2 ± 19.0 L, 84.5 ± 9.6 L H_2O-e and 16.0 ± 1.6 m^3, and 7.6 ± 0.1 m^2/kg C eggs, 1.4 ± 0.03 kg CO_2-e, 12.0 ± 0.3 MJ, 190.6 ± 23.1 L, 88.9 ± 10.3 L H_2O-e and 17.5 ± 1.9 m^3, and 8.1 ± 0.1 m^2/kg CF eggs and 1.5 ± 0.04 kg CO_2-e, 12.2 ± 0.3 MJ, 204.6 ± 23.9 L, 100.8 ± 10.7 L H_2O-e and 19.1 ± 1.8 m^3 and 8.7 ± 0.1 m^2/kg FR eggs. Land use and direct land use-change emissions associated with imported soymeal were significant, contributing a further 0.6 ± 0.1, 0.7 ± 0.1 and 0.7 ± 0.1 kg CO_2-e/kg C, CF and FR eggs respectively. More efficient feed conversion ratios (FCRs) drove lower impacts in C production. Feed production was the major hotspot, followed by the layer farm and pullet rearing operations. **Conclusions.** Reducing impacts will be most effective through changing diets to reduce reliance on high environmental-impact feed commodities, FCR improvements and energy efficiency measures to reduce housing energy demand. Improved land management is likely to have resulted in isolated small levels of carbon sequestration in Australian cropland over the analysis period, offsetting some GHG emissions. Further reduction in environmental impacts will rely on decarbonisation of feed supply chains and prioritisation of low environmental-impact feed commodities. **Implications.** Being the first industry-wide environmental assessment of Australian egg production, this study has highlighted the need for ongoing assessment to isolate inter-annual variability, determine long-term trends, and investigate pathways to reduce impacts into the future.

Keywords: carbon footprint, eggs, greenhouse gases, land use change, life cycle assessment, sustainability indicators, sustainable agriculture, water stress.

Introduction

Transparent and coherent sustainability credentials for industries and food products have become a major expectation of consumers and governments worldwide (Miller *et al.* 2017). Sustainability is a broad concept, extending from environmental to socio-economic aspects (WCED 1987). The international poultry industry and the Australian egg industry have identified climate action as a priority issue (International Poultry Council and FAO 2019; Australian Eggs Limited 2022). Further to this, energy, water and land are also key resources for agri-food production systems and have been identified as long-standing priorities for Australian life cycle-assessment (LCA) research (Harris and Narayanaswamy 2009), reflecting a broader national imperative and trend towards mitigating environmental impacts.

LCA has become the predominant tool for comparing multiple environmental impacts from product systems, such as eggs, to similar food products. LCAs of egg production, conducted across multiple jurisdictions, have found that eggs are a relatively low impact protein product relative to other animal derived products (see Williams *et al.* 2006; de Vries and de Boer 2010; Clune *et al.* 2017). For Australian systems, Wiedemann and McGahan (2011) reported greenhouse gass (GHG) impacts that were similar or slightly lower than those reported in international egg LCAs, with the majority of impacts arising from feed production and the layer farm. The study used data from 2008 to 2010 and covered two production systems (cage and free-range) from three large-scale farms in the south-eastern region of Queensland and the northern region in New South Wales. It was not comprehensive for Australian production and did not report impacts for land use and direct land use-change emissions, water stress or land occupation. This study, established to address these gaps, and quantify impacts for cage, cage-free and free-range eggs for the Australian industry, focused on environmental impacts as one key area of sustainability assessment. It assessed carbon, fossil energy, freshwater consumption and stress, and land-occupation impacts which were globally and regionally relevant to egg production. More generally, the study is fundamental to supporting future improvement in industry performance, the identification of major impact sources and production processes that influence environmental performance, and the investigation of pathways to reduce impacts into the future. The study responds to broader emerging market and economy-wide priorities and initiatives.

In 2021, the Australian Government delivered a Long-Term Emissions Reduction Plan for net-zero economy-wide GHG emissions by 2050 (Commonwealth of Australia 2021*a*). This technology-driven approach aims to facilitate emission reduction by lowering the cost of existing and emerging technologies and accelerating their adoption. The development and cost reduction of alternatives to fossil energy, such as ultra low-cost solar, energy storage and low-emission fuels (Liquefied natural gas, uranium), are positioned as significant steps in Australia's pathway to net zero. Understanding the contribution of fossil energy to the emission profile of Australian egg production is the first step in assessing how decarbonisation of energy supply will benefit the Australian industry.

Further emissions, and in some cases sequestration, arise from land use and direct land-use change, which are also closely related to agriculture (Commonwealth of Australia 2021*b*). Agricultural industries face the challenge of increasing production to meet consumer demand, while concurrently reducing impacts. For the Australian egg industry, which has grown by 14.5% since the 2016–2017 financial year (AEL 2021), any further growth will require a substantial reduction in the emission intensity of eggs just to maintain total emissions. Critical to making progress in this area is this comprehensive performance baseline, including GHG-emission hotspots within the egg industry, and ongoing reporting to track emissions over time.

Hotspots for indicators other than carbon covered in this study are significant for their wide-reaching and varied affects. Water stress, particularly that due to spatial and temporal fluctuations in water supply and demand, has been reported to affect four billion people worldwide for at least 1 month each year (Mekonnen and Hoekstra 2016). Many river basins, including in the Australian Murray–Darling Basin, exhibit counter-cyclical water consumption and availability, i.e. consumption is greatest when availability is lowest, which, according to Mekonnen and Hoekstra (2016), may result in decreased flows, and reduced groundwater and lake water levels. This has far-reaching consequences. Freshwater consumption and stress impacts arise within the operational boundary of the egg industry but also within and because of operations in other industries (grain), which then flow through to egg production.

Land management is another environmental issue of critical importance in Australia and abroad, and is once again an environmental indicator where egg production is exposed to impacts arising outside its operational boundary. The way land is managed and the extent it is used have major effects on ecological systems, food production, climate change, and water; appropriate use is fundamental to effective responses and management of existing and emerging climatic and environmental issues (Lesslie and Mewett 2013). To determine the scope for improvement, quantified analysis is essential to understanding the direct impacts of the egg industry on land and those that arise in upstream feed-grain production.

Materials and methods

Goal and scope

The goal of this study was to determine baseline environmental impacts for the 2019–2020 financial year for Australian egg production across different housing systems. An attributional LCA (aLCA) model was applied to quantify carbon, fossil energy, freshwater consumption and stress, and land-occupation impacts for cage (C), barn [cage-free (CF)] and free-range (FR) eggs, assessed using primary-industry data from major production regions.

In C systems, hens are housed in tiered cages and conveyer belts are used to transport feed, eggs and manure in and out of sheds. In CF systems, manure and eggs are also typically removed from the shed via conveyor belts. The sheds typically have multiple tiers of slats for birds to perch on and the floor may be mesh, slats or litter, or a combination of these. In FR systems, hens are housed in sheds with litter, and have access to an outdoor range during the day.

Inventory data were collected from 22 farms across three housing systems in six states, representing 40% of national supply. The distribution of surveyed farms matched major production regions as closely as possible, but some regions were under-represented and others over-represented compared with national statistics for layer hen distribution. To account for this, the inventory was weighted to reflect the national supply chain (see Supplementary material Table S1) and the inventory data-summary tables in the following sections are the weighted average data. Regionally sensitive inputs, such as electricity used from a particular state energy grid and grain, were weighted according to the national distribution of egg production. For each producer, grain was assumed to be sourced from the nearest major grain-producing region, unless the specific region was identified during inventory data collection, and then weighted according to the national distribution of egg production.

Impacts assessed

The study assessed GHG emissions by using the IPCC AR5 global warming potentials over 100 years (GWP_{100}) of 28 kg carbon equivalents (CO_2-e)/kg for methane (CH_4) and 265 kg CO_2-e/kg for nitrous oxide (N_2O), as applied in the National Greenhouse Accounts (Commonwealth of Australia 2021*b*). In accordance with ISO 14067 (ISO 2018), GHG emissions associated with land use (LU) and direct land-use change (dLUC) were included and reported separately.

Demand for fossil fuel energy was assessed by aggregating all fossil energy inputs throughout the foreground and background system and reporting these per megajoule (MJ) of energy, using lower heating values.

As described in the subsequent sections, freshwater consumption (L) was assessed using methods consistent with ISO 14046 (ISO 2014). Irrigation water-supply losses were also assessed. Water Account Australia (ABS 2021*a*) gave the sources of irrigation water supply as distributed sources, bores, other surface-water supplies and re-use water from other industries. Supply losses from distributed irrigation sources were specified in the national water account (ABS 2021*a*). The average loss rate for the 2018–2019 and 2019–2020 financial years was 13% (ABS 2021*a*). These losses correspond to evaporation losses from state-owned supply dams and seepage losses from irrigation channels. Losses from surface-water sources and bores were assumed to be negligible and were not included (see Wiedemann *et al.* 2015 for details).

Stress-weighted water use was assessed using the following two methods: the water stress index (WSI; Pfister *et al.* 2009) and the available water remaining method (AWARE; Boulay *et al.* 2018), reported in L H_2O-e and m^3 respectively. Both aim to quantify the impact of water consumption on the basis of the relationship between total freshwater consumption and freshwater availability; however, AWARE is a measure of water availability after production-driven consumption and then after subtracting the broader requirements of human and aquatic ecosystems, whereas WSI assesses blue water (surface and groundwater) consumption along the production chain. Regions with scare water resources and/or high demand have high levels of water stress.

Land occupation was assessed by aggregating impacts throughout the supply chain and was reported in square metres (m^2).

Although an extensive range of environmental indicators could have been assessed in addition to those selected, the study covered impacts that were deemed most significant for Australia, and that have high weightings in international systems, such as the product environmental footprint (Directorate-Generale for Environment 2021). Assessment of eutrophication, eco-toxicity and impacts to human health require regional characterisation factors which have not been developed for Australia (Renouf *et al.* 2018). Hence, at the present time, analysis of these indicators was not included, but future work in these areas would be warranted to provide a broader environmental analysis.

All modelling was performed using SimaPro™ 9.3 (Pré-Consultants 2021) and the study applied an attributional modelling approach.

Supply chains, system boundary and functional units

Production from six Australian states and three housing systems was investigated. Data were collected for the study for a 12-month period from 1 July 2019 to 30 June 2020, from seven major egg producers, covering pullet rearing, layer farm and grading. The supply chain included breeding and hatchery processes, pullet rearing, and layer farms through to grading floors (see Fig. 1), with all associated inputs (see Table S2).

Data were de-identified and aggregated to ensure that company data were confidential and to provide broader, industry-wide (rather than state-specific) benchmarking.

The end-point of the supply chain was the cold storage unit where eggs are stored prior to wholesale distribution, which was located at the grading site. Results were reported relative to 1 kg of eggs ready for wholesale distribution. In addition, results were reported per kilogram of shell- and protein-corrected eggs, ready for packaging and distribution to retail. The shell correction factor was determined using shell mass as a percentage of fresh egg mass (13.6%), derived from Clarke and Wiedemann (2020). Impacts were then adjusted for edible protein of the egg pulp (13.5%) to allow for comparison with boneless, protein-adjusted meat products. In effect, the protein adjustment corrected the mass difference by removing the higher moisture content in eggs.

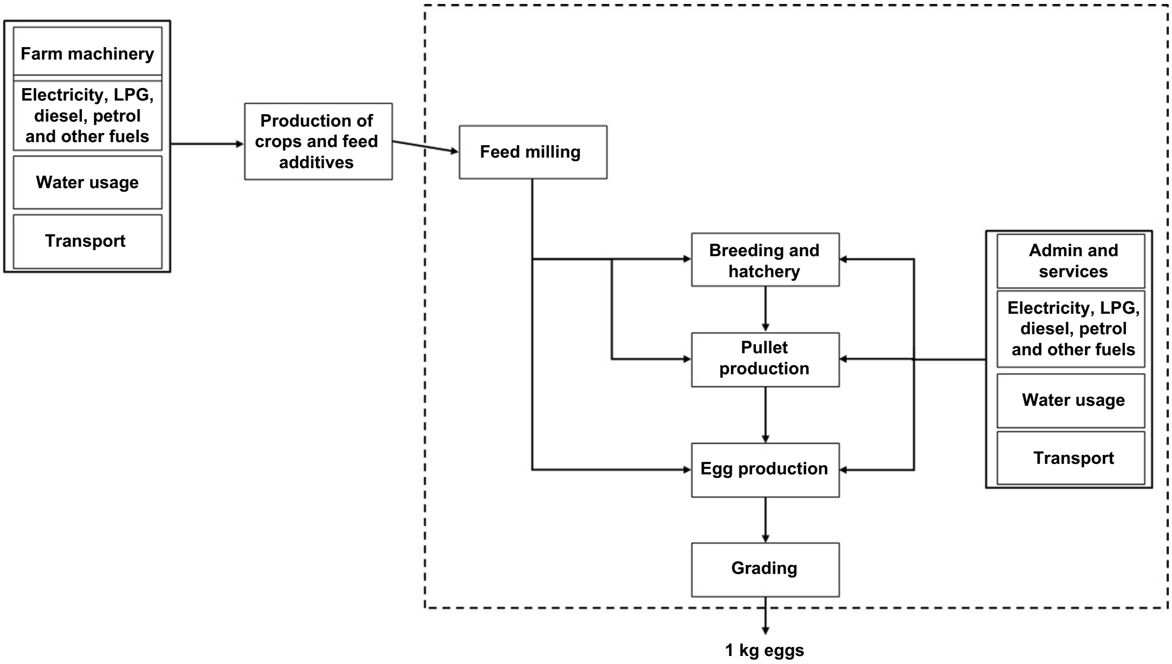

Fig. 1. System boundary for egg production (dotted line denotes foreground system).

Life-cycle inventory

Feed use and milling

Ration data for layers and pullets were reported by the companies while existing datasets from Wiedemann and McGahan (2011) were used for breeder feed composition. Producers who operated their own feed mill reported energy and water use, and transport distances over 12 months (Table 1).

Birds are phase-fed, and feed composition may vary due to changes in the availability of feed commodities. The aggregated layer ration is shown in Table 2, where less commonly used inputs (though modelled individually) are grouped under general headings for conciseness. Average pullet diet composition is reported in Table S3.

Feed production

Major feed grains were modelled from Australian grain processes from the AusLCI database (ALCAS 2017), where available (see Table S4), with modification to account for water consumption and water stress by the authors in representative state markets for feed grains used in egg production. Average irrigation rates in each region and the proportion of cropland irrigated were used to determine the proportion of cereal grains produced in dryland and irrigated systems (ABS 2021*b*, 2021*c*). Each process included the supply losses associated with the provision of irrigation from rivers, bores, and dams. Grain processes were then aggregated into markets for the major cereal grains produced in each state, which reflected the location and distribution of the nearest major grain production to egg production regions. These processes applied emission factors from the Australian National Inventory Report (NIR; Commonwealth of Australia 2021*c*) to determine field GHG emissions from grain production.

Table 1. Major feed-milling inputs ($n = 4$), reported per 1000 kg of feed produced.

Input	Average of mills surveyed	Range
Grid electricity (kWh)	6.3	6.0–6.7
Solar-generated electricity (kWh)	1.9	0.0–3.8
LPG (MJ)	1.5	0.0–3.7
Diesel (L)	0.02	0.0–0.1
Freshwater (L)	33.3	26.5–41.0
Transport (t km)	84.1	0.5–200.0

Accounting for emissions from LU and dLUC in the Australian grain system was difficult because specific datasets that disaggregate impacts from one crop to the next were not available, as noted by Sevenster *et al.* (2020). To understand the likely sign of change in soil carbon, the minimum recommended analysis period is one full-crop rotation (ISO 2018); however, considering that carbon changes occur over longer time periods influenced by management and season, a longer averaging period may be warranted. In this study, national average datasets from the Australian National Inventory Report (NIR; Commonwealth of Australia 2021*c*) were used to determine emissions and sequestration over the 5 years preceding the inventory time period (2015–2019), reflecting the change in soil carbon attributable to cropping. Total carbon change over

Table 2. Commodity inputs (*n* = 8) per 1000 kg of ration for layers in cage, cage-free and free-range production.

Commodity	Cage	Range	Cage-free	Range	Free-range	Range
Wheat (kg)	262.7	15.4–565.5	221.0	15.4–528.6	343.0	15.4–565.5
Barley (kg)	50.5	19.2–100.0	45.3	19.2–100.0	55.3	19.2–100.0
Sorghum (kg)	331.3	0.0–628.5	387.7	0.0–628.5	238.3	0.0–638.6
Other cereals and grain by-products (kg)	6.3	0.0–21.8	5.7	0.0–21.8	5.8	0.0–21.8
Soybean meal (kg)	92.3	39.2–161.7	94.7	39.2–133.5	90.4	39.2–161.7
Canola meal (kg)	71.5	40.0–105.2	66.5	40.0–105.2	80.8	37.7–105.2
Plant oils (kg)	14.0	0.0–44.4	12.2	0.0–44.4	15.2	0.0–44.4
Other plant protein, e.g. field peas, lupins (kg)	25.6	0.0–102.0	21.8	0.0–102.0	23.3	0.0–102.0
Animal protein meals (kg)	36.4	0.0–54.9	35.9	26.8–54.9	36.4	0.0–54.9
Tallow/poultry oil (kg)	1.4	0.0–3.6	1.7	0.0–3.6	0.7	0.0–3.6
Low-cost additives, e.g. salt, lime (kg)	98.3	93.0–105.6	97.7	93.0–105.6	100.1	76.4–105.6
High-cost additives, e.g. synthetic amino acids, enzymes, premixes (kg)	9.6	4.5–17.5	9.7	4.5–17.5	10.6	3.7–17.5
Total	1000.0		1000.0		1000.0	

this time period was summed, amortised and reported as an annual value for 2020, a method considered appropriate to avoid unusual seasonal influences on soil carbon sequestration or loss. Sequestration was observed in the most recent 5-year period of 2015–2019 (−135 kg CO_2-e/ha, negative value reflecting removal of CO_2 from the atmosphere). This may be reflective of long-term changes in crop management in Australia, from cultivation to zero tillage and stubble retention, which can increase soil carbon (Luo *et al.* 2010). The impact of assessing a 2-year (with sequestration rate of −145 kg CO_2-e/ha) and 10-year (with a rate of carbon loss of 34.2 kg CO_2-e/ha) time sequence was considered as part of the sensitivity analysis.

Imported soybean meal was modelled using data from the ecoinvent database (Ecoinvent 2020), on the basis of the relative soybean meal imports where South America was the dominant market (98%) with the next largest source, the United States, representing 0.2% of the total imports (OEC 2019).

Where model processes were unavailable for some small dietary inputs constituting less than 3% of the diet, substitutions were made with other feed inputs, as in Wiedemann and McGahan (2011) and Copley and Wiedemann (2022). As described by Wiedemann *et al.* (2012), feed inputs requiring substitution were typically low-cost products associated with low levels of manufacturing and high-cost products that were typically associated with high levels of manufacturing and transportation. The substitution ratio was informed by economic value and known processing requirements: low-cost inputs (e.g. salt) were substituted for other mined products such as lime, and high-cost inputs (e.g. enzymes) were substituted for synthetic amino acids.

Breeding and pullet production

An Australian average breeding process was developed from previous datasets (see Table S5; Wiedemann and McGahan 2011) and pullet data were developed from inventory data collected from producers (see Tables S5, S6). Water use was collected from farm records and water was predominantly used for drinking and cleaning, and in some cases, for evaporative cooling. After ingestion, drinking water was respired, excreted with manure, or integrated into the bird or egg. Thus, drinking water was treated as freshwater consumption. Likewise, cleaning water was considered a consumptive use; small volumes of water were used for cleaning and sheds were left to dry out afterwards.

Layer farm phase

Australian average performance data and farm inputs for layer hens were developed from the inventory data. Flock performance, including feed intake and total eggs produced, was determined from records supplied by each company and represent actual performance under commercial conditions (shown alongside major inputs in Table 3). Records of water use, energy use, and litter management were collected from all farms. Water-use volumes were collected from farm records and were handled as described for the breeding phase.

Manure management

A mass balance, based on feed and bird production data, was used to estimate manure excretion. Manure GHG emissions (CH_4, N_2O) and indirect emission precursors [ammonia (NH_3)] were estimated by predicting nitrogen (N) and volatile solids (VS) excretion by using mass balance principles and by applying emission factors for birds housed in litter and non-litter systems from the National Inventory Report (Commonwealth of Australia 2021*c*), including

Table 3. Australian average performance data and farm inputs (*n* = 18) for layer hens.

Item	Cage	Range	Cage-free	Range	Free-range	Range
Performance data						
Feed conversion ratio (kg layer feed/kg eggs)	2.1	2.0–2.4	2.3	2.2–2.4	2.4	2.2–2.8
Inputs (reported per 1000 kg eggs produced)						
Grid electricity (kWh)	155.9	94.5–243.3	226.8	149.5–336.3	222.1	83.0–328.5
Solar-generated electricity (kWh)	4.4	0.0–26.5	3.0	0.0–12.0	57.8	0.0–104.5
LPG (MJ)	2.4	0.0–7.8	4.0	0.0–13.8	7.0	0.0–28.2
Diesel (L)	3.1	0.2–12.8	3.5	1.8–5.5	1.5	0.0–2.8
Fresh water (L)	6259.0	3162.1–8028.3	7159.0	5430.9–12 685.0	7855.4	2967.7–12 856.1

state-specific factors for manure CH_4 and emissions from range areas. For the mass balance, N inputs were determined from inventory data collected from egg producers for daily feed intake and diet specifications. Subtracting N inputs (in feed) from N outputs in bird mass, mortalities and eggs gave excreted N; N retention determination used methods previously described in detail by Wiedemann and McGahan (2011) and for chicken meat in Wiedemann *et al.* (2016*a*), and the same conceptual model was used here. Excreted VS was determined by subtracting manure ash from excreted total solids, which represented the residual of non-digested feed (Dong *et al.* 2006). VS excretion-rate determination has also been described in detail by Wiedemann and McGahan (2011).

Manure was typically sold as a low-value fertiliser and soil-amendment product and was therefore treated as a residual, meaning no allocation of impacts from egg production was given to the manure (see Handling co-production; LEAP 2016).

At the farm level, indirect N_2O was modelled from NH_3 volatilisation. All sheds were assumed to be constructed with impervious floors according to environmental regulations, and therefore nitrate leaching from sheds was assumed to be negligible. Leaching and runoff in range areas were modelled using regionally specific factors (Commonwealth of Australia 2021c) and the fraction of manure (14%) deposited in the FR area (Clarke and Wiedemann 2020).

Cage production was modelled for sheds where birds were housed without litter and all manure was removed on belts. In cage-free systems, birds were housed either in sheds with slats where manure was removed via conveyor belts, or barns where manure was deposited on the floor with litter and remained until the end of the batch. In free-range systems, all sheds were litter-based and received 86% of manure deposited. Across all housing systems, the majority (75–80%) of manure or spent litter was sold-off farm after being stored on-site for a period of time (typically <3 months) until it was suitable to spread to land. Emissions from stockpiling this manure were included in the boundary of the study. The remaining manure was treated by composting prior to land application. Composting emissions were not included in the boundary of the study, as these were considered an emission associated with producing the composting product and were attributable to the system using the compost.

Grading

Grading data were collected from six grading floors operating across five states. Most grading operations used water from reticulated supplies; only two relied on bore water. Water at grading floors was treated as freshwater consumption. Two grading floors sourced some or all of their electricity demand from renewable sources (solar). Major inputs associated with grading are reported in Table 4.

Handling co-production

Co-products from the system included manure and spent hens. Manure was a low-value output from the system and was treated as a residual, meaning no allocation process was applied and impacts from manure following removal from the sheds were assumed to be attributed to the system using it as a fertiliser (LEAP 2016). A small proportion of manure may be used back on land that is used to grow grain for feeding layer hens, resulting in potentially lower fertiliser requirements for grain and reducing environmental impacts. Through discussion with producers, the volume of manure used in this way was expected to be modest, and tracing this manure application and displaced synthetic fertiliser through to grain production for layer and pullet feed was not feasible. A conservative assumption was applied, assuming no reduction in synthetic fertiliser arising from manure use, which was a conservative assumption. Spent hens were

Table 4. Grading inputs (*n* = 76) reported per 1000 kg eggs graded.

Input	Average from grading floors surveyed	Range
Grid electricity (kWh)	58.4	0.0–122.2
Solar-generated electricity (kWh)	6.0	0.0–37.1
LPG (MJ)	105.2	0.0–182.2
Diesel (L)	0.1	0.0–0.3
Fresh water (L)	1078.7	366.7–1802.8

typically processed for human consumption. Allocation of impacts between eggs and spent hens was therefore performed on the basis of edible protein mass [biophysical allocation, which is the recommended method in the LEAP poultry guidelines (2016)] in hens and eggs, resulting in 4% allocation of impacts to meat from hens.

The shell- and protein-correction to eggs corrected the mass difference between eggs and other animal proteins by removing the shell, higher moisture content and normalising on protein. No impacts were allocated to the shell or water. In the feed-supply chain, economic allocation processes were used to determine impacts to protein meals and oil products, such as, for example, canola meal and oil, and soymeal and oil (see Wiedemann *et al.* 2016*b*). For rendered products, such as meat meals, impacts associated with manufacturing were attributed to the rendered product. The raw material (bones, fat) were treated as residuals from the original meat processing system and no impact was transferred to these residual products, in accordance with guidance (LEAP 2015).

Sensitivity analysis

The sensitivity of the model to key assumptions and parameters was tested. Methodological details for the sensitivity analyses are outlined in Sensivity analysis methodology in the Supplementary materials.

Uncertainty

After Leinonen *et al.* (2012), two types of uncertainties (alpha and beta) were considered in the input variables, where alpha uncertainty describes the variations among farms reflecting the primary datasets and beta uncertainty describes the uncertainties in the model. Alpha and beta uncertainty were assessed using a Monte Carlo analysis in SimaPro (Pré-Consultants 2021), using 1000 iterations to provide a 95% confidence interval (CI) for results.

Results are presented using the mean and the standard deviation, and both alpha and beta uncertainties were used to calculate the CI.

Alpha uncertainties included all layer farm, grading and mill inputs and production data, and feed composition. Beta uncertainties included housing-specific manure factors, and breeding and hatchery operation processes.

As beta uncertainty was shared by all systems, comparison of the mean results between housing systems was based on alpha uncertainties only, and significant differences were determined using the following equation of Wiltshire *et al.* (2009):

$$z = \frac{100 \times |A - B|}{\sqrt{\mathrm{CV}_B^2 \times A^2 + \mathrm{CV}_B^2 \times B^2}}$$

where A, B are the mean values and CV_A and CV_B are coefficients of variance of the two systems compared.

Results

Impacts per kilogram of eggs

Greenhouse gas emissions (excl. LU and dLUC) were 1.2 ± 0.04 kg CO_2-e/kg eggs for C production, 1.4 ± 0.03 and 1.5 ± 0.04 kg CO_2-e/kg eggs for CF and FR production respectively (refer to Fig. 2). Emissions from LU and dLUC were 0.6 ± 0.1 kg CO_2-e/kg eggs for C production, and 0.7 ± 0.1 kg CO_2-e/kg eggs for both CF and FR. The carbon footprints (GHG incl. LU and dLUC) were therefore 1.8 ± 0.1, 2.1 ± 0.1 and 2.2 ± 0.2 kg CO_2-e/kg eggs for C, CF, and FR respectively. After accounting for shared uncertainty, impacts were significantly different for all production systems.

LU and dLUC emissions were from soybean production on recently converted cropland in South America (associated with high levels of soil carbon loss). As imported soybean meal inclusion rates in feed did not differ greatly among systems (refer to Table 2), LU and dLUC emissions were similar. Carbon sequestration (denoted as negative LU and dLUC emissions) in Australian cropland amounted to −0.09 kg CO_2-e/kg eggs, and was included in the total LU and dLUC impacts.

Layer feed production was the hotspot for GHG emissions, with impacts ranging from 52% to 56% excluding LU and dLUC, and from 69% to 72% of impacts including LU and dLUC. Emissions from the layer farm were 23–26% of the total, excluding LU and dLUC, or 15–17% including LU and dLUC, where energy use for housing and manure emissions were the major contributors. For free-range production, emissions from manure (deposited on ranges and in sheds) contributed 0.16 kg CO_2-e/kg to the carbon footprint, compared with 0.12 kg CO_2-e/kg in C production, with the elevated manure impacts from FR being related to higher estimated nitrous oxide emissions from the range area. Grading contributed 7–8% excluding LU and dLUC and 4–5% including LU and dLUC, where the major emission source was fossil energy. Pullet production (including pullet feed production) represented 11–13% of emissions (excluding LU and dLUC) or 7–8% (including LU and dLUC), where the major sources were fossil energy use and emissions from manure. The significant difference among C, CF and FR systems was related to elevated FCR in the non-cage systems resulting in higher feed-related impacts, and in the case of FR, slightly higher manure-related emissions.

Fossil energy use was 10.7 ± 0.2 MJ/kg from cage production, 12.0 ± 0.3 and 12.2 ± 0.3 MJ/kg for eggs from CF and FR production respectively. After accounting for shared uncertainty, impacts were significantly different between C, and CF/FR systems; CF and FR were not significantly different. Layer feed production accounted for 55–58% of fossil energy use, with most energy related to field operations and fertiliser manufacture in grain production and feed-related energy was the principal driver

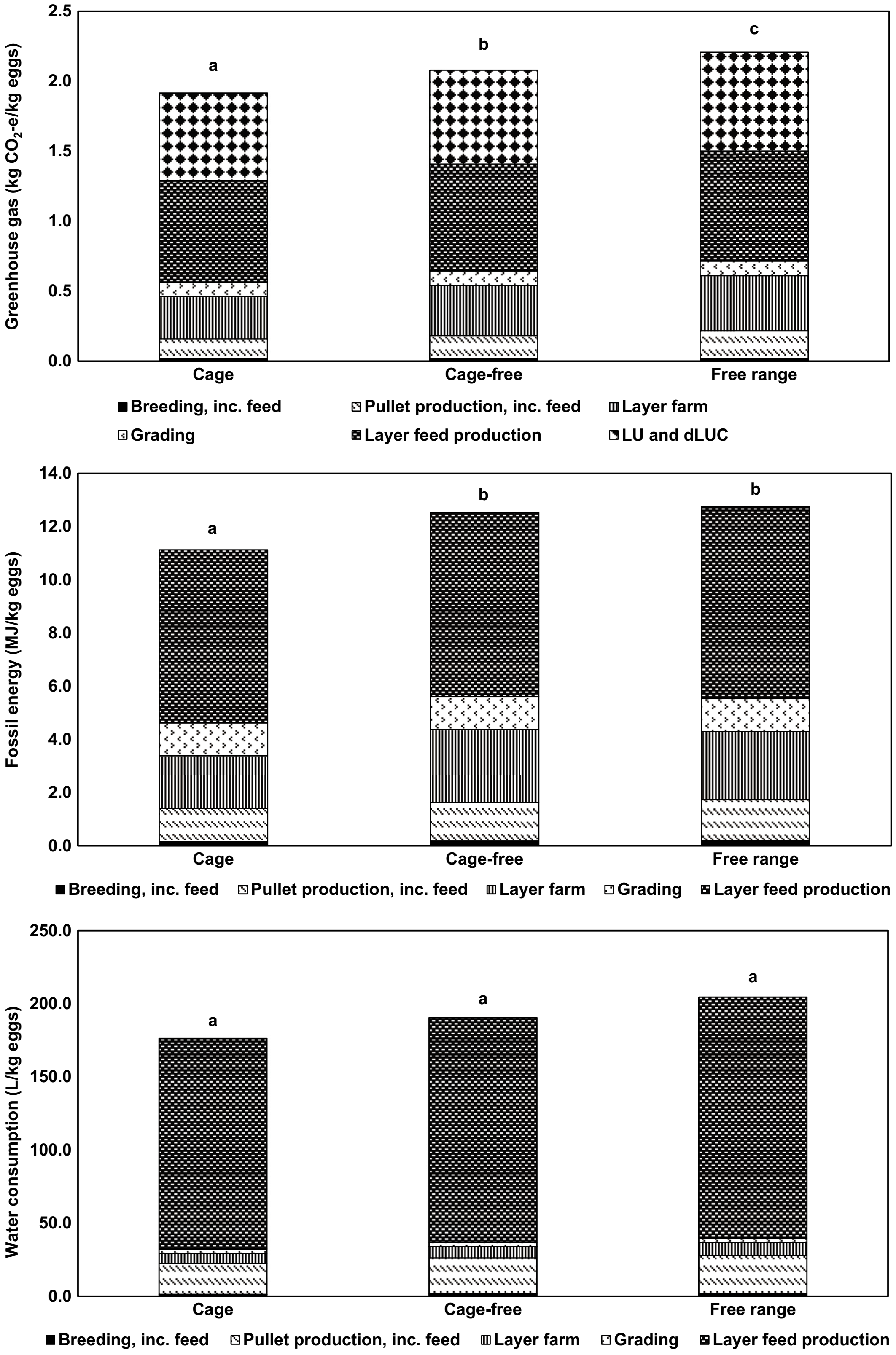

Fig. 2. Greenhouse-gas emissions, fossil energy and freshwater consumption from cage, cage-free and free-range eggs. Greenhouse-gas results are inclusive of LU and dLUC impacts. Different letters on bars indicate significant differences between total impacts assessed by Monte Carlo analysis based on the alpha uncertainty and Wiltshire *et al.* (2009).

of higher energy from CF and FR production, which had slightly higher FCRs than did C systems. The layer farm (18–22%) was the next major source of energy demand, followed by pullet production and pullet feed production (11–12%), and grading (10–11%).

Freshwater consumption ranged from 177.2 ± 19.0 to 190.6 ± 23.1 L/kg eggs for C and CF production systems, and 204.6 ± 23.9 L/kg eggs for FR production. Water used for layer feed production, especially irrigation, accounted for 81–82% of consumption. Drinking and cooling at the layer farm represented 4% of total water and pullet production, including pullet feed, 12–13%, whereas grading (1–2%) contributed a smaller amount.

Under the WSI method, stress-weighted water use was 84.5 ± 9.6 and 88.9 ± 10.3 L H_2O-e/kg eggs in the C and CF systems, and 100.8 ± 10.7 L H_2O-e/kg eggs for FR production. Using the AWARE method, water use was 16.0 ± 1.6, 17.5 ± 1.9 and 19.1 ± 1.8 m^3/kg eggs for C, CF and FR systems respectively. Irrigation water (for all feed production) represented 94% of the stress-weighted water use assessed under the WSI method, averaged across the three systems. Under the AWARE method, irrigation water for all feed production represented 69% of stress-weighted water use, averaged across the three systems. For both water consumption and water stress, apparent differences among production systems were not statistically significant. There was an apparent trend in higher water use for CF and FR systems because of the higher FCR in these systems and because of small differences in diet.

Land occupation was 7.6 ± 0.1 and 8.1 ± 0.1 m^2/kg eggs for the C and CF production systems, and 8.7 ± 0.1 m^2/kg eggs for FR production. Arable land occupation for feed production represented 99% of the total land occupation. After accounting for shared uncertainty, impacts were significantly different for all production systems. Production system differences were related to FCR and distribution-related factors, resulting in different land intensity impacts among the production systems.

Impacts per kilogram of shell-corrected eggs

Impacts per kilogram of shell- and protein-corrected eggs are shown in Table 5. Results were ~36% higher than for eggs in shell because of the loss of mass associated with the shell-corrected product and the adjustment for protein content.

Sensitivity analysis

The sensitivity of the results to production region and state grid emission intensity was tested and analysis showed that, for a model farm (which operated feed milling and grading), the carbon footprint of eggs produced in Tasmania was up to 0.2 kg CO_2-e lower than if the farm operated in Victoria (Vic.), Australia's lowest and highest emission intensity energy grids respectively (see Tables S7, S8).

The sensitivity of the results to FCR showed that a 0.1 improvement in FCR (relative to Australian averages in Table 3) reduced impacts across all indicators in C, CF and FR production (Table S9, relevant data denoted as C1, CF1, and FR1). Impacts declined by 3% (GHG, water stress, water scarcity) and 4% (freshwater and land occupation). In addition, analysis showed that a 10% reduction in dietary crude protein reduced GHG emissions (excl. LU and dLUC) by 2% for FR (denoted as FR2).

In this study, unless informed otherwise, grain was assumed to be sourced from the nearest major grain-producing region(s) to the egg-producing farm. The sensitivity of this assumption was tested (see Table S10) by comparing impacts for a model New South Wales (NSW) cage producer who (in the control scenario) sourced all grain from major local regions with alternative sourcing scenarios. Scenario A where 50% of grain was sourced from Western Australia (WA) to simulate the impact of severe grain shortage and much larger transport-distance requirements resulted in 5% higher (relative to the control scenario) fossil energy impacts (from transport), lower freshwater consumption (29%), stress (45%) and scarcity (11%) but higher land occupation (27%) and GHG (excl. LU and dLUC) emissions (4%) per kilogram of eggs (Table S10). Scenario C (for a mixed eastern seaboard grain market) was associated with lower (27%) freshwater consumption, water stress (51%) and scarcity (17%) but higher fossil energy consumption (10%), land occupation (29%) and GHG emissions (excl. LU and dLUC) (4%) per kilogram of eggs (Table S10) than was the control scenario. The results demonstrated that freshwater consumption, water stress, scarcity and land occupation were the

Table 5. Resource use and impacts for eggs for cage, cage-free and free-range production, reported per kilogram of egg edible, protein-corrected product (excluding shell mass).

Item	Fossil energy (MJ)	Freshwater consumption (L)	Stress-weighted water (L H_2O-e)	AWARE water (m^3)	Arable land (m^2)	Greenhouse gases, excl. LU and dLUC (kg CO_2-e)	Greenhouse gases, LU and dLUC (kg CO_2-e)	GHG total (kg CO_2-e)
Cage	14.9	205.4	94.4	20.9	10.1	1.7	1.0	2.7
Cage-free	16.9	224.4	103.4	23.7	10.8	1.9	1.0	2.9
Free-range	17.0	234.3	112.8	24.9	11.6	2.0	1.0	3.0

parameters most sensitive to assumptions regarding sourcing of cereal grains.

The sensitivity of the results to methodological choice of a 5-year analysis period for soil carbon change in Australian cropland was tested through comparison with a 2-year period and a 10-year period. Analysis showed that, for the 2-year period of 2018–2019, carbon sequestration in Australian cropland was slightly greater at –0.10 kg CO_2-e/kg eggs but that the 10-year period of 2010–2019 was associated with soil carbon losses equivalent to 0.02 kg CO_2-e/kg eggs (Table S11).

Discussion

This study established a national baseline for environmental performance in the egg industry, which is fundamental to underpinning the ability of the industry to quantify impacts and communicate performance improvements across environmental priority areas.

Main impact sources in the supply chain

For all three production systems, and across all indicators, feed production was the major impact source. Of this, cereal grains were the greatest contributor to all indicators, except LU and dLUC. In this study, the emission intensity of layer feed (averaged across the three systems) was found to be 0.37 kg CO_2-e/kg (excl. LU and dLUC). For comparison, the rations reported by Wiedemann and McGahan (2011) were re-analysed and the emission intensity, in AR5 values, ranged from 0.27 to 0.28 kg CO_2-e/kg. In comparison, emission intensities of layer feed in a study by Leinonen *et al.* (2012) ranged from 0.748 to 0.785 kg CO_2-e/kg for organic and non-organic production.

A significant driver behind the difference in emission intensity between the current study and that published in 2011 was the increased N_2O emissions reported in Australian cereal grain production over the past decade. For example, Brock *et al.* (2012) reported the emission intensity of wheat produced in central NSW as 0.2 kg CO_2-e/kg, while the more recent study by Simmons *et al.* (2019) found that, for wheat from the same region, the emission intensity was 0.315 kg CO_2-e/kg (both in AR4 values), an increase of more than 50%. Although not necessarily indicative of an actual increase in emissions, the finding in Simmons *et al.* (2019) was based on improved insight into key emission factors and production systems, leading to higher reportable emissions for cereal grain. More generally, Simmons *et al.* (2019) also reported the emission intensities of cereals produced in 13 other regions, all of which were higher than the intensity reported by Brock *et al.* (2012) in their single region case study.

This suggests that, as the reported emission intensity of Australian wheat is higher than previously understood, previous studies (including that of Wiedemann and McGahan 2011) may have inadvertently underestimated impacts. At present, the Australian feed grains sector is yet to release a strategy for emission reduction, meaning that there is no short-term indication whether a decrease in the emission intensity of feed grains (and the emission intensity of poultry feed) can be expected.

The water and land footprints of egg production were also highly exposed to upstream impacts from feed production. As most land occupation was attributable to arable uses, the key variable that influenced arable land use was crop yield. Crop yields varied between source regions and irrigation rates. Irrigation resulted in a trade-off between water and land, which trended in opposite directions when comparing irrigated and non-irrigated grain, i.e. high levels of irrigation were associated with low levels of arable land occupation, and *vice versa*. Accordingly, water consumption, stress-weighted water use, and the emission intensity of feed exhibited considerable regional variation based on the prevalence of irrigation.

Although domestically produced feed grain accounted for a considerable proportion of impacts, with the exception of water consumption, impacts were relatively low when compared with imported soybean meal. This high-protein, low-cost commodity (relative to its amino acid profile) is a dietary staple and is in high demand within the egg, chicken meat and pork industries (Willis 2003). More broadly, global demand for the major export commodity from South America has driven a rapid expansion in production and the conversion of pasture or forest to cropland (Arrieta *et al.* 2018), leading to substantial GHG emissions from dLUC. Most imported soybean meal in the Australian feed market is now derived from South America, compared with a decade ago where a greater volume came from the United States (OEC 2019). There is a substantial difference in emission intensity between soybean meal produced in the USA (GHG emissions of 0.28 kg CO_2-e/kg, and LUC of 0.0001 kg CO_2-e/kg) and that produced in Brazil and Argentina (0.43 kg CO_2-e/kg, and LU and dLUC impacts of 3.27 kg CO_2-e/kg; Ecoinvent 2020).

Although complete or partial substitution of high-impact imported soybean meal for accredited soybean meal or for alternative proteins, such as field peas, animal or canola meals, would reduce LU and dLUC emissions, challenges or trade-offs may emerge as a result. First, the reformulated rations would likely be higher cost, meaning higher selling price of eggs would be required to maintain profitability. Second, though LU and dLUC impacts may be reduced through substitution of imported soybean meal, the alternative protein source may increase impacts across other indicators. Cottonseed meal, for example, is a by-product of a production system that requires very high levels of irrigation, meaning that the commodity has a high water footprint. Further research is needed to understand and reduce impacts via substitution of diet ingredients to reduce reliance on soymeal. An alternative method to reduce impacts from imported soymeal is for soy-exporting nations to develop management practices that reduce or eliminate this loss of soil carbon (from converted pastureland) and deliver accredited soymeal without dLUC impacts to markets that increasingly expect low environmental-impact products.

Emissions and sequestration reported for cropland in the Australian NIR showed no change in average annual emissions associated with the conversion of forest land to cropland (here described as dLUC). As soil carbon concentrations may vary significantly from year-to-year, averaging over a long timeframe, such as the 10 years in the sensitivity analysis, may disguise that variability and be less representative of soil carbon change for a specific analysis period (Sevenster *et al.* 2020). In the most recent 5 years to 2019, carbon losses from dLUC in Australia have moderated and sequestration in crop soils has increased, resulting in net sequestration (of −135 kg CO_2-e/ha), amounting to −0.09 kg CO_2-e/kg eggs, reducing the carbon footprint of eggs by approximately 5%. Given uncertainty as to whether sequestration in Australian cropland will continue over time, and the magnitude of the LU and dLUC impacts from imported soybean meal, the scope for reducing these emissions to reduce the carbon footprint of egg production is (based on the current data) largely confined to soybean meal.

The greatest influence on the contribution of feed, including feed commodities such as imported soybean meal, to impacts was FCR. If FCR improved, impacts were reduced across all environmental indicators; poorer FCRs resulted in comparatively high impacts across all indicators (as in FR production). However, for an individual facility, the effects of FCR improvement were not uniform due to the influence of other factors, such as climate. In particular, farm water consumption exhibited significant variation across the industry due to climatic differences among major production regions. For the industry more broadly, the market-driven phasing out of cage production (the most efficient system) means that total environmental impacts may increase in the future. For customers and consumers, this highlights a trade-off between perceived welfare improvements on one hand and an increased environmental footprint of eggs on the other.

Reported FCRs in this study were higher than those in Wiedemann and McGahan (2011), even for farms included in both studies. Changes in management to optimise production to meet consumer preferences (for larger eggs), changes in feeding to improve animal welfare in non-cage systems and longer housing periods were associated with the increase in FCRs. With the phasing out of cage production in Australia, further increases in industry-average FCR appear likely unless there are significant advances in genetics or feed formulation to compensate for the higher feed requirement of birds raised in these systems. On the basis of the current trends and transition to meet future regulatory requirements, these advances will be fundamental to the ability of the industry to maintain or reduce impacts in future.

After feed production, the most significant contributions to GHG emissions, energy and water consumption occurred at the layer farm and pullet-rearing facility. Emissions from layer and pullet manure were directly correlated with FCRs (more feed, more manure), but scenario analysis found that reducing dietary crude protein (CP) by 10%, from 17.4 to 15.7% for layers and pullets resulted in a modest reduction in emissions from manure; in FR systems the reduction in dietary CP resulted in a 2% reduction in the emission intensity (excluding LU and dLUC of eggs; Table S9). Alternatively, emissions may be reduced at the farm-scale through improved manure management (e.g. installing manure belts in slat-based sheds) to reduce ammonia losses prior to land application of manure.

The other major source of emissions was fossil energy consumption (itself an environmental indicator). Although many farms drew a portion of their energy requirements from renewable sources (solar), this represented only a small fraction of the total industry electricity demand and so did not have a substantial effect on either average fossil energy consumption or GHG emissions of eggs. Scenario analysis was conducted to determine the GHG mitigation potential (and fossil energy use reduction) per kilogram of eggs from electricity from solar for a model Queensland-based producer of CF eggs who milled feed and graded eggs on-site. Using electricity generated on-site (equivalent to 40% of total electricity demand) resulted in 10% lower fossil energy use, 8% lower GHG excluding LU and dLUC (or 4% lower for GHG incl. LU and dLUC) per kilogram of eggs (see Table S12). The results of the analysis indicated that substantial reductions in on-farm fossil energy consumption and GHG emissions are possible through adoption of on-site renewable energy generation; however, targets for decarbonisation of electricity grids suggest that offsetting high emission-intensity grid electricity with on-site generated renewable electricity will result in decreasing reductions in emissions over time.

Grading and breeding phases (when feed production was excluded from the latter) accounted for the least impacts across all indicators. Fossil energy consumption (particularly grid electricity) was the greatest source of GHG emissions for both. Two of the grading floors in this study drew some or all of their electricity demand from renewable (solar) sources. For the breeding phase, excluding feed production, fossil energy and manure were the greatest sources of emissions, with the former largely used for cooling, heating and lighting.

Freshwater consumption and total electricity consumption at layer farms were lowest in cage systems and highest in free-range. Aside from FCR influences, eggs per hen per year were also greatest in the cage system and lowest in the FR system, meaning that (all other things being equal) it takes less of each input to produce 1 kg of eggs in cage production than it does to produce CF or FR. Lower bird density in the CF and FR systems also contributed to higher energy requirements for housing, as did the use of older sheds with less efficient sealing for CF production than for C production, resulting in higher ventilation requirements. It was noted that the contribution from renewable electricity was highest in FR systems, possibly because many were newer developments than the C and CF systems. This reduced the impact of higher energy use in FR substantially.

Comparison with the previous Australian study

The previous Australian study reported environmental impacts for egg production in 2010, covering two regions only (Queensland (Qld) and NSW) and utilised data from three farms, each producing C and FR eggs (Wiedemann and McGahan 2011). In contrast, the present study included producers from all major regions, three production systems, and was based on data collected from some 40% of the industry. Although the previous assessment did not cover the breadth of the industry, it was a valuable study with which to compare results per kilogram of graded eggs.

Per kilogram of eggs, impacts were found to have remained relatively unchanged for energy and GHG (excl. LU, dLUC). The contributions to the carbon footprint were relatively consistent with the 2010 assessment, the notable phases being feed production, pullet production and the layer farm. As discussed previously, one observable counter trend, increased reported impacts from Australian cereal grains, resulted in an increased emission intensity of feed. Although fossil energy consumption was not found to have reduced over the decade, there was evidence of adoption of renewable energy generation on farms and at grading floors.

Freshwater consumption was higher than reported by Wiedemann and McGahan (2011). The present study was a weighted average of a greater number of state markets for feed grains and a greater number of catchments. The drought effect on the proportion of irrigated versus dryland grain in feed was the most significant driver behind the apparent increase in water consumption. The anomalous nature of the assessment period and the influence on the baseline results highlighted the need for recurring assessments so that a less extreme benchmark can be established.

Wiedemann and McGahan (2011) did not report land occupation or stress-weighted water use nor did the authors report LU and dLUC results in their assessment. However, analysis of the original inventory data indicated that LU and dLUC impacts for the C and FR supply chains in that assessment would have been 0.4 and 1.6 kg CO_2-e/kg eggs respectively (compared with the 0.7–0.8 kg CO_2-e in this assessment) had soymeal been imported from South America instead of the United States. The ration for cage production in the previous study contained 77.4 kg of imported soybean meal per 1000 kg of feed, and the FR ration contained 258.4 kg per 1000 kg of feed. The difference between the LU and dLUC impacts for eggs from cage production indicated that, even where inclusion rates of imported soybean meal have fallen since 2010, impacts per kilogram of feed, and eggs were much greater.

Regional differences

The regions assessed in this study exhibited variation in fossil energy and water consumption. The contribution of grid electricity to the carbon footprint of eggs was heavily influenced by the proportion of a state's electricity derived from fossil energy (as opposed to renewable) sources, which was directly correlated with the energy grid's emission intensity (see Sensitivity analysis).

At the farm (layer, rearer or breeder), water consumption was heavily influenced by climatic conditions. Consumption was lowest in states that experience the coolest weather; states with hotter climates had a higher consumption due to the need for cooling to maintain ideal conditions for birds. Similarly, energy demand varied among regions. Higher energy demand due to heating requirements were typically reported by producers operating in states with cooler weather (data not shown for confidentiality reasons).

Regional differences in ration composition were also observed. However, whether rations were sorghum-based (common in northern production regions) or wheat-based (south and west) did not have a substantial effect on environmental impacts. Rather, whether grain used in rations was irrigated or not was the most significant driver in regional variation in the environmental impacts of feed production. Drought conditions on the eastern seaboard during the analysis period resulted in low grain supplies, and, consequently, a greater proportion of the cereal grains were from irrigated production systems, resulting in a very high water consumption per 1000 kg of feed. The increased proportion of irrigated grain in feed was atypical and the net result may have increased the water intensity of eggs. Water consumption in the NSW and Qld average wheat markets for feed in the egg industry was 84.0 and 134.4 L/kg wheat (and had WSIs of 80.5 and 65.8 respectively). This shows that, although consumption was higher in Qld, the regions in NSW from which wheat was sourced were under considerably greater water stress. The AWARE indicators (11.5 and 10.9 m^3 respectively) aligned with this. In comparison, water associated with the average WA wheat market for egg industry feed was 4.3 L/kg wheat, with a WSI of 2.9 H_2O-e/kg, because the vast majority of WA wheat is grown in dryland conditions.

The drought conditions on the eastern seaboard in 2020 meant that some supply chains relied, at least in part, on grain brought from WA to the eastern states for feed. For an egg producer, the net result reduced the water intensity of feed but increased the GHG emission intensity and fossil energy footprint (due to large transport distances). Wheat produced in predominantly dryland production in WA had slightly higher GHG emission intensity (0.34 kg CO_2-e/kg wheat) than did wheat from NSW (0.32 kg CO_2-e/kg wheat) but the sensitivity testing for grain source region (Table S11) suggested that transport distances drove the difference in fossil energy and GHG emission intensity in feed more than did cropping practices.

Comparison with international LCA

Comparison between LCA studies, even for similar industries or products, is complicated due to differences in assessment methods, assumptions, and system boundaries. The comparison made here for GHG does not include LU and dLUC impacts as these were not typically assessed in the comparison studies.

Per kilogram of C, CF and FR eggs, mean GHG emissions in the present study were lower than in most other studies (Williams *et al.* 2006; Leinonen *et al.* 2012; Pelletier *et al.* 2014; Ghasempour and Ahmadi 2016; Abín *et al.* 2018; Turner *et al.* 2022), with few exceptions. The exception was a review of LCA studies (Clune *et al.* 2017) where the lowest reported value for the carbon footprint of eggs was equal to the 1.3 kg CO_2-e for cage eggs reported by Wiedemann and McGahan (2011).

Differences in the emission intensity of feed were the most significant driver behind the comparatively low emission intensity of Australian eggs. The average emission intensity of layer feed in the present study was 0.37 kg CO_2-e kg/feed, which was substantially lower than those of the United States (0.58 kg CO_2-e kg/feed; Pelletier *et al.* 2014) and the United Kingdom (non-organic: 0.785 kg CO_2-e/kg feed; Leinonen *et al.* 2012). Due to zero-till farming and comparatively low rates of fertiliser application and field emissions of nitrous oxide, feed commodities produced in Australia are typically lower-impact products, resulting in comparatively low emission factors. Although crop yields are relatively low as a result, as zero-till farming is the norm in Australia, fossil energy impacts per 1000 kg of grain are typically significantly lower than those of other production systems.

Mean fossil energy consumption per kilogram of eggs in this study was similar to the value for the USA (12 MJ; Pelletier *et al.* 2014; Pelletier 2017), and well under that reported for Iran (30.9 MJ; Ghasempour and Ahmadi 2016) and also lower than fossil energy consumption per kilogram of eggs given by Williams *et al.* (2006; 13.6 and 15.4 MJ for cage and FR, adjusted from GJ per 1000 kg of eggs) and Leinonen *et al.* (2012) for the UK (16.88–22.20, excl. organic eggs and adjusted from GJ per 1000 kg of eggs).

Freshwater consumption, where reported, did not include water used for irrigation in feed production; i.e. the values were for foreground water consumption only. For Australian production, freshwater consumption, excluding water used for feed production, per kilogram of eggs was 11.2 (±1.2), 12.4 (±1.5) and 13.4 (±1.6) L for C, CF and FR respectively. The range in consumption (5.11–5.35 L) for UK C, CF and FR eggs (Leinonen *et al.* 2012) for direct water-use water (drinking and cleaning, no water from crop production) was much lower than was consumption in this study, which is likely to be related to lower temperatures in the UK, reducing water requirements for cooling compared with Australia.

No studies reported stress-weighed water use using either WSI or AWARE factors. However, Wiedemann *et al.* (2017), in a LCA of Australian chicken meat production, noted that stress-weighted water use would presumably be greater as there is more demand for water for cooling and irrigation in Australia than in several other regions with cooler climates. Given the significant similarities between egg and chicken meat production systems and supply chain hotspots for water, it is reasonable to assume that WSI and AWARE factors for Australian egg production may well be greater than those for many other countries.

Few studies reported land occupation footprints for eggs. For those that did, due to significantly lower crop yields in Australia, the land occupation footprint of Australian eggs was higher than (Pelletier 2017) for C, CF and FR eggs in the UK (4.0, 4.2, and 5.1 m^2 respectively), but lower than for eggs from organic systems (16.9 m^2; Leinonen *et al.* 2012). Similarly, Williams *et al.* (2006) found land occupation per kilogram of C and FR eggs was 6.3 and 7.8 m^2 respectively (adjusted from hectares), compared with 14.8 m^2 for organic eggs.

A further factor contributing to the comparatively low emissions from Australian egg production is that the Australian National Greenhouse Accounts (Commonwealth of Australia 2021*b*), due to low moisture levels and the nitrogen deficiencies typical of Australian soils, applies a factor to determine indirect nitrous oxide (from ammonia volatilisation) that is an 80% lower factor than the default IPCC value (Gavrilova *et al.* 2019).

This study, in accordance with Wiedemann and McGahan (2011), found that FR production was a slightly higher-impact system (across all indicators) than was C production. This was consistent with the findings of some comparative studies (Williams *et al.* 2006; Leinonen *et al.* 2012; Pelletier 2017; Turner *et al.* 2022). Free-run systems, equivalent to CF production in the present study, were found by Turner *et al.* (2022) to have an emission intensity similar to (enriched or conventional) that of C production, but a lower emission intensity than for FR production.

In terms of statistical significance, Leinonen *et al.* (2012) also found that primary energy use and GHG emissions were significantly lower in C systems than in barn, FR and organic systems, and that results were driven by feed efficiencies in each system. The authors did not find significant differences between CF and FR production. Turner *et al.* (2022) found that, from an environmental perspective, that conventional cages generally outperformed alternatives and that the phasing out of conventional cage systems may result in a net negative for the environmental sustainability of the Canadian egg industry.

Comparison with other animal proteins

Per kilogram of shell- and protein-corrected eggs, GHG emissions (excl. LU and dLUC) were lower than for boneless Australian chicken meat (2.6–2.8 kg CO_2-e; Copley and Wiedemann 2022) and the national average for Australian boneless pork (6.5 kg CO_2-e), and substantially lower than for boneless Australian beef (29.5 kg CO_2-e) and lamb (18.3–20.8 kg CO_2-e; Wiedemann 2018). Similarly, fossil energy consumption was lower than the fossil energy footprints for boneless beef, lamb, pork, and chicken meat. Although arable land occupation for eggs was substantially higher than for boneless beef and lamb, the extensive nature of Australian grazing systems means that total land occupation for egg production was far lower. This is consistent with the trend identified for boneless chicken meat (Copley and Wiedemann 2022), although arable land occupation for eggs was lower. Stress-weighted water use (WSI) was lower than all four comparison meat proteins; however, AWARE values for boneless chicken meat were in some instances relatively similar to (although still higher than) those for the shell- and protein-adjusted eggs. Freshwater consumption fell within the range for boneless chicken meat and was substantially lower than for boneless beef. Therefore, compared with other Australian animal proteins, eggs are one of the low environmental-impact products.

GHG mitigation

Technologies and management strategies targeting feed-related impacts include reducing inclusion rates of high-impact imported soybean via substitution with alternative proteins meals or certified soy, and FCR improvement (see Wiedemann and McGahan 2011) have the potential to substantially reduce the environmental impact of egg production. Adoption of renewable energy or energy-efficiency measures could be investigated to reduce fossil energy consumption and, by extension, emissions. Carbon storage and sequestration opportunities may arise from manure deposited on ranges, from tree planting (see Ramachandran Nair *et al.* 2010; Doran-Browne *et al.* 2016) and from the application of manure to land. Reducing emissions from manure may be possible through reducing dietary CP (see Wiedemann *et al.* 2016*c*), or through strategies such as covering stockpiles (see Naylor *et al.* 2016), and fertiliser replacement or nutrient recovery (see Jenkins *et al.* 2015; Pratt *et al.* 2016). Waste-to-energy technologies, such as anaerobic digestion, may be viable options to better manage manure and generate energy provided the manure or spent litter feedstock is appropriate (see Baranyai and Bradley 2008; McGahan *et al.* 2013; Pratt *et al.* 2015; Tait and Batstone 2016), although implementation in poultry has been shown to be more difficult than for pigs.

A comprehensive assessment of all technologies and management strategies is needed to identify the technical mitigation potential, compatibility with other technologies or practices, and the economic implications of adoption. While some technologies are mature and proven in the Australian egg industry (e.g. solar), others, even if adopted overseas, require further investigation to determine their viability in the Australian context.

In line with their emission reduction targets, state governments have set targets to decarbonise energy grids by increasing the relative contribution of renewable sources of electricity. The extent to which the industry can rely on this to reduce GHG emissions in unclear. A quantified and projected analysis is needed to model the emission intensity and total emissions of Australian egg production.

Conclusions

A staple source of protein, Australian eggs are, across a range of indicators, a relatively low-impact protein product, particularly in respect to GHG emissions. Cage production was found to result in the lowest environmental impacts across all categories and FR the highest, although in practical terms, the differences were relatively modest. This noted, it does demonstrate a trade-off in expectations as industry moves from C to CF and FR systems in response to market expectations; there will be slightly higher impacts on the environment that must be mitigated.

However, a shared challenge across all production systems is that the cheapest source of protein for feed, imported soymeal, is also the highest environmental-impact feed commodity. Any transition to alternative protein sources or certified soybean meal is likely to increase the cost of production. Given the comparatively low margins of egg production, any change from least-cost production could be expected to place upward pressure on the selling price for eggs.

After imported soybean meal, the industry is critically exposed to feed grain production for its contribution to the carbon, water, land use, and energy profile of eggs. Improved management practices of cropland (relative to historical practices) in the years prior to the analysis period resulted in moderate levels of carbon sequestration in Australian cropland which, when carried through to grains used in layer feed, may have offset approximately 5% of the carbon footprint of eggs, a short-term correction to soil carbon concentrations due to improved land management. Interannual climatic variability, including drought, may significantly affect the land occupation, water consumption and stress impacts arising from grain production and, by extension, eggs; regular updates to benchmarking are needed as interannual effects can be both positive and negative.

Solutions to these challenges are required for the egg industry in Australia and globally to continue to meet the food demands of a growing population without causing negative environmental outcomes. These baseline impacts provide the foundation for the development of a robust, long-term sustainability framework to track and report the performance and environmental credentials of the industry into the future, supported by thorough investigation of the mitigation potential and feasibility of emission reduction technologies and management practices.

Supplementary material

Supplementary material is available online.

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Author affiliation
[A]Integrity Ag and Environment, 10 Neil Street, Toowoomba, Qld 4350, Australia.