Determining manure deposition in free range sheds and free range areas

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Foreword

This project was conducted to assist free range egg producers with the management of manure nutrients to minimise the risk of environmental impacts. The research is part of the ongoing investment by Australian Eggs Limited in research that underpins environmental best practice guidelines for the Australian egg industry. Integrity Ag & Environment is an agricultural and environmental consultancy with experience conducting research for, and extending research to, the Australian egg industry.

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

This report is an addition to Australian Eggs Limited's range of peer reviewed research publications and an output 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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Printed copies of this report are available for a nominal postage and handling fee and can be requested by phoning (02) 9409 6999 or emailing research@australianeggs.org.au.

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Abbreviations

DW	Dry weight
LW	Live weight
P	Phosphorous
N	Nitrogen
n	Number
NATA	National Association of Testing Authorities, Australia
SD	Standard deviation
TS	Total solids
VS	Volatile solids

Executive Summary

Poultry farmers have an environmental duty of care to manage manure nutrients to minimise the risk of environmental impacts. Previous research on free range farms showed that nutrients are concentrated within a short distance (0–10 m) from sheds despite birds having the opportunity to range much further (Wiedemann et al. 2018). This manure distribution pattern interacts with site features (such as climate, soil profile, ground water depth and distance to waterways) to determine the risk of nutrient loss. However, it is not known what proportions of the total nutrients are deposited inside and outside a free range shed, making estimation and management of nutrient deposition difficult and uncertain.

Accordingly, the objective of this research was to determine manure nutrient excretion in a free range shed via mass balance. That is, to predict manure nutrient excretion in the range area by the difference between predicted nutrients excreted by the bird and measured nutrients deposited in the shed. The research took place on two commercial free range sheds on the Darling Downs, Queensland. Both sheds were populated with over 27,000 layer hens for 69 (Shed A, Hy-Line Brown) or 60 (Shed B, ISA Brown) weeks, with outdoor stocking densities of 7000–7300 hens per hectare. Samples taken of feed, water, eggs, manure, and soil composition, were combined with company production data and supplemented with data on carcase composition to quantify nutrient inputs and outputs.

For conservative analytes (i.e. phosphorous, potassium and ash), the mass observed in manure ranged from values approximately equal to predicted excretion, or were lower. Focusing on phosphorous, for Shed A, the excretion rate to the range area was not significantly different to zero - it would need to be 11.6% to be significant. For Shed B, the excretion rate was significantly greater than zero (10.4%) and less than 19.9% at the upper limit of the analytical uncertainty. While some uncertainty remained from the results, the most conservative interpretation was that outside excretion was less than 20% of total excretion. When results for all conservative analytes were combined, the most likely excretion rate to the range area was 7.2%. Based on these results, 7.2% could be considered a reasonable excretion rate for nutrients from free range sheds that are of a similar size and management system to those assessed here. We note that extrapolating these results to the whole industry is limited by potential differences in ranging behaviour by birds in different housing and ranging environments across Australia. The results showed that ca. 40–50% of the predicted nitrogen excretion, and the vast majority (> 80%) of the volatile solids in the predicted excreta, were emitted to the atmosphere or deposited in the range area. If the rate of nitrogen deposition in the range was 7.2%, 33–41% of nitrogen was an emission to the atmosphere, which was expected to occur primarily via ammonia volatilisation. The manure results showed an unexpected high concentration of ash (ca. 50%). A follow-up analysis showed that ca. 28% of the manure for Shed B was silica, which was used to infer that ca. 30% of the manure was soil, which was an unexpected finding. These results were used to identify the practical implications of the work to industry, and to prioritise areas for further research.

Using the results presented in this report, it is relatively simple for industry to estimate the deposition of manure in range areas. The rates and masses of nutrients excreted in the range area were consistent with previous observations of ranging behaviour and international research, which supports the continued use of current industry practices for managing nutrients in range areas. The findings of this research should be used to update the next edition of the industry environmental guidelines, particularly the observation of unexpectedly high manure ash and silica concentrations and their potential implications. The inferred rate of soil transport out of the range and into the shed has potential implications for range management – range rehabilitation (e.g. filling of holes) will be required if the soil export rate is high, and the maintenance of groundcover will increase in importance. Further research should identify the mechanism/s responsible for transporting soil into

free range sheds and evaluate how widespread this phenomenon is. Because geophagy (the ingestion of soil) is a possible mechanism, a risk assessment is recommended for new and existing farms to assess the potential for hazardous materials in soil to have negative impacts on bird health and food safety.

Overall Conclusions and Recommendations

Conclusions

- For Shed A, the phosphorous mass balance results showed an excretion deposition rate in the range area of less than 11.6% of total excretion, and for Shed B, this rate was less than 19.9%. Results for all conservative analytes (i.e. phosphorous, potassium and ash) showed it is most likely that 7.2% of predicted excretion will be deposited in the range area of free range sheds that are of a similar size and management system to those assessed here. These results can be considered a reasonable excretion rate for nutrients from free range sheds, though extrapolating these results is limited by potential differences in ranging behaviour by birds in different housing and ranging environments across Australia. These deposition rates are equally applicable to non-conservative analytes co-deposited in excreta, such as nitrogen and volatile solids.
- Uncertainty in the proportion of predicted excretion deposited in the range area is principally driven by the analytical uncertainty of concentration data for the largest input and output – feed and manure, respectively. The need to use relatively incomplete *post hoc* silica concentration data to estimate soil inputs to the system introduced additional uncertainty, despite the observed concentrations being entirely consistent with published values.
- Predicted excretion can be estimated from dry matter digestibility, which can be estimated from published or industry data, multiplied by expected feed consumption. These simple calculations provide a means for industry to estimate the deposition of manure in range areas.
- The observed nutrient deposition rates were consistent with literature on hen behaviour and international research on nutrient deposition rates in range areas. This is important because it supports the continued application of current industry recommendations for managing nutrients in free range areas. However, there may be a need to consider anew the potential volume of soil brought into free range sheds from range areas and the implications of this transport on bird health, productivity, food safety and range rehabilitation.

Recommendations

- Further research is recommended to define (1) the ash and silica concentrations in the manure of a larger sample of free range production systems, and (pending this result) (2) the mechanism/s that result in elevated ash and silica concentrations and the implications of this on food safety, bird health, productivity and the environmental management of range areas. An industry survey of the chemical composition of manure in free range sheds, annotated with relevant contextual information, would be a straightforward means of identifying management × environment interactions with high manure ash contents, with the added benefit of placing the current research in context.
- A comprehensive set of predicted excretion rates on range areas for other regions, management systems, and stocking densities requires further research.
- Considering the potential of these results to indicate reasonably high levels of soil consumption by free range hens, a precautionary approach to managing risks from soil contamination is recommended for new and existing free range sites. We recommend conducting a risk assessment to assess the risk of potentially hazardous materials in range area soils, to avoid the potential for negative bird health and food safety outcomes.
- It is recommended that the data reported in this report on the manure composition of free range production systems be used to update the next edition of the *Egg Industry Environmental Guidelines* (McGahan et al. 2018).

1 Introduction

1.1 Background

Free range production represents approximately 56% of the egg industry by value (Australian Eggs Limited 2019). This project is focused on improving environmental management and planning in the free range sector by assisting new farm developments and building the knowledge base around acceptable management practices for range areas. There are some sensitive aspects regarding range areas: particularly that nutrient control requirements can be costly and disadvantageous for other reasons (i.e. biosecurity implications if dams are required), and that soil monitoring is also a small cost that may not be required at some facilities if the nutrient deposition is very low. There is now some knowledge regarding soil nutrient levels (Wiedemann et al. 2018), but less knowledge about how they might change over time, because annual deposition rates are not known. Thus, doubt remains in this area.

Poultry farmers have an environmental duty of care to manage manure nutrients to minimise the risk of environmental impacts (Wiedemann et al. 2018). A survey of free range farms showed that nutrients are not evenly distributed across range areas. Instead, they are concentrated within a zone a short distance (0–10 m) from sheds despite birds having the opportunity to range much further (Wiedemann et al. 2018). This manure distribution pattern interacts with site features (such as climate, soil profile, ground water depth and distance to waterways) to determine the risk of nutrient loss (Wiedemann et al. 2018). Management options should be developed to respond appropriately to these risks. For example, water movement across inner range areas (0–3 m) should be minimised by using verandas, and nutrient enriched runoff from the 0–10 m zone should be managed to minimise environmental impacts. At greater distances (> 10 m), nutrient monitoring and management options such as nutrient removal via crop production may be acceptable practices (Wiedemann et al. 2018).

While the research cited above identified the pattern of nutrient deposition in free range areas, two knowledge gaps persist. Firstly, it is not known exactly what proportion of the total nutrients are deposited inside and outside a free range shed, making estimation of nutrient deposition difficult and uncertain. The simplest way to make this calculation is to begin with bird numbers and make predictions of manure nutrient excretion. This method is used in all other intensive livestock industries in Australia to help guide design and development of new farms (e.g. Tucker 2018). However, in the egg industry this information is not known. The second gap relates to the amount of nutrients lost from the site in runoff, which is an important indicator of off-site risk. This project addressed the first of these gaps only.

1.2 Objectives

The objective of the research was to determine manure nutrient excretion in a free range shed via mass balance, and predict manure nutrient excretion in the range area by the difference between excreted nutrients and nutrients deposited in the shed.

2 Materials and methods

2.1 Experimental approach

Mass balance is a reasonable way of predicting manure excretion and in this case, proportional deposition in/out of the shed (von Bobrutzki et al. 2013; Migliavacca & Yanagihara 2017). Briefly, the mass balance approach requires quantification of inflows (e.g. feed, water, hens) and outflows (e.g. eggs, hens, shed manure) to/from one or more commercial free range sheds (described in full in Section 2.9). The difference between these flows represents mass lost from the system. These losses may be to the atmosphere (in the case of volatile compounds) or to the range area. Ideal compounds for quantifying manure deposition on the range area are therefore non-gaseous (i.e. conservative); not water, nitrogen or dry matter – which can be lost via evaporation, denitrification/volatilisation or respiration, respectively. Ideal compounds will also maximise the signal to noise ratio to minimise measurement uncertainty. Thus, our focus was on key nutrients (phosphorous and potassium) and ash (the residue after heating a sample at high temperature). The authors have completed a similar study on commercial broilers (conventional sheds) for the Australian meat chicken industry (Wiedemann et al. 2016) and for deep litter pigs (Phillips et al. 2016). A short mass balance trial was also completed for the layer industry focused on caged sheds (Wiedemann et al. 2015). These studies provided a strong basis for applying similar research methods.

2.2 Production system characteristics

The research was focused on two free range production sheds on the Darling Downs, south-eastern Queensland, Australia. These sheds, A and B, were located on the same property, had an indoor footprint of approximately 2600 m^2 each, began operating in 2011, and had an outdoor range stocking density of 7000–7300 hens per hectare. Above a cement floor, the sheds had a raised mesh floor with perches and nesting boxes. The sheds did not utilise bedding material and were evaporatively cooled. Both sheds had an inner range area of approximately 0.75 ha, approximately evenly split north and south of the elongated (130 m) sheds. The inner range area was denuded of vegetation except for native tree plantings along boundary fences. Portable metal frames (10 × 2 m, $n > 12$) covered in shade cloth were used to promote ranging behaviour in the inner range. An outer range area extended to the east of both sheds. An additional set of shade cloth structures ($n = 4$) was used in the first portion of the outer range area (> 3 ha), which included a dirt service road and a broad unimproved pad used to temporarily deposit manure removed from the sheds. Beyond the pad, the outer range was vegetated with native grasses and trees.

At 15 weeks of age, on the 23rd of November 2018, a flock of 27,122 Hy-Line Brown layer hens was introduced to Shed A. Daily opening and closing of the pop holes at 10:00 and 20:30, respectively, began 45 days later. Depopulation of Shed A began on the 9th of March 2020, at a flock age of 83 weeks.

At 17 weeks of age, on the 3rd of May 2019, a flock of 27,135 ISA Brown layer hens was introduced to Shed B. Daily opening and closing of the pop holes at 10:00 and 20:35, respectively, began three weeks later. Depopulation of Shed B began on the 15th of June 2020, at a flock age of 76 weeks.

Water supplied to both sheds came from the same bore. Feed was produced by the company using a local milling operation that used target specifications based on hen breed, system and flock age. The feed included granulated limestone as a grit and calcium source.

2.3 Production data

All production data were provided by the collaborating company. Feed intake was determined from daily silo weights and water intake was determined from daily water consumption by mid-afternoon (multiplied by 24/15 to convert to a daily total). Egg production (number, weight) and hen mortalities were obtained from company records. The company recorded average hen weight weekly until a flock age of 30 weeks, thereafter it was recorded at a flock age of 50 and 70 weeks.

2.4 Weather data

Weather data were obtained from a Bureau of Meteorology station accessed via the SILO database (https://www.longpaddock.qld.gov.au/silo/point-data/). The station was ca. 3 km from the site.

2.5 Soil and water sampling and analysis

At the project outset (prior to population of Shed A), soil samples were obtained on the north and south sides of both sheds, at a distance of 8 and 18 m from the pop holes. Soil samples were submitted for analysis for depth intervals of 0–30 cm and 60–90 cm.

A single sample of drinking water was obtained for each shed when the shed was populated. Given the water was sourced from a single bore, the standard deviation between the two sets was used to represent the uncertainty.

2.6 Feed sampling and analysis

Feed samples were taken from the hoppers inside the shed. One sample from each shed was submitted for analysis approximately monthly over the first 9 months for Shed A, and first 4 months for Shed B. Thereafter this was carried out approximately every two months. Measurement uncertainty was estimated by analysing one batch of feed in triplicate.

2.7 Egg and carcase composition

Egg and carcase composition were assumed to be constant between the sheds. Egg composition (and associated uncertainty) was based on triplicate analyses of eggs sampled from the production facility. Carcase composition was based on unpublished data (Wiedemann & McGahan unpublished Egg-Bal model). Uncertainty in carcase composition was based on values reported in the peer-reviewed literature (Webster et al. 1998).

2.8 Manure sampling and analysis

The company completed depopulation over approximately three days. After depopulation, company staff used bobcats to remove accumulated manure from the shed and to deposit it in a pile in the outer range area. Contractors then used a loader to remove the manure by truck (e.g. to cropland within the site or farmed by a third party).

Using a hand spade and bucket, manure was alternately sampled from the top and bottom third of the manure pile (a) approximately every 3 m around its initial perimeter, and then (b) approximately every 2 m across the fresh face revealed by the loader, as manure was loaded into the truck. Each bucket load of manure was transported to a plastic tarpaulin. The tarpaulin was used to minimise contamination of the sampled manure with soil and to protect the manure from wind and direct light.

Once the manure pile had been sampled, the sub-sample on the tarpaulin was thoroughly mixed using a shovel then placed in ~1 kg lots into zip-lock plastic bags. Large feathers were removed from each bagged sample. The samples were transported on ice then refrigerated prior to shipping to a NATA accredited laboratory for analysis.

Manure samples were analysed for phosphorous, potassium, ash, moisture, and nitrogen concentration. To minimise nitrogen losses, nitrogen was determined using the Kjeldahl method on fresh (not oven-dried) samples (Mahimairaja et al. 1990). Uncertainty was quantified by analysing samples in triplicate.

Manure weights were obtained using a weighing loader (model 930H, Caterpillar) fitted with a bucket payload weighing sensor. Truck mass was verified by weighing four representative truckloads of manure over a commercial weigh bridge. The linear regression between these measurements was used to correct the weighing loader measurements ($y = 0.97x + 0.85$, $r^2 > 0.99$). The root mean-square error (± 0.34 t) of this relationship was used to represent the uncertainty in manure weights.

2.9 Mass balance calculations

As mentioned above (Section 2.1), a mass balance approach was used to estimate manure deposition on the range. Cumulative compound mass (m_j) of a pool (subscript j, such as feed) was determined by summing compound concentration ($[m_{ij}]$) times pool mass (m_{ij}) across all time increments (subscript i) in the production cycle:

$$m_j = \sum_{i=1}^{n} [m]_{ij} \cdot m_{ij} \qquad \text{Eqn 1}$$

This approach estimated predicted excretion from inputs less outputs. For example, for phosphorous (i.e. m = P):

$$\mathrm{P}_{predicted\ excretion} = \mathrm{P}_{feed} + \mathrm{P}_{water} + \mathrm{P}_{hen\ LWin} - \mathrm{P}_{eggs} - \mathrm{P}_{hen\ LWout} \qquad \text{Eqn 2}$$

Where LW = liveweight in or out. For a conservative compound, predicted excretion on the range was the difference between predicted excretion and recovered manure. For phosphorous:

$$\mathrm{P}_{predicted\ excretion\ on\ range} = \mathrm{P}_{predicted\ excretion} - \mathrm{P}_{manure\ recovered} \qquad \text{Eqn 3}$$

All values were reported as means ± SD. Uncertainty was carried through the calculations using algebraic error propagation. The error propagation calculations were verified by Monte Carlo simulation (n = 1000 iterations). To synthesise the deposition rates observed for different analytes across both sheds into a single value, the mean and uncertainty of each analyte-shed combination was used to derive six normal probability frequency distributions. Giving each distribution equal weighting, these normal distributions were summed to derive a single probability frequency distribution for the results as a whole.

2.10 Soil fraction in manure calculations

The manure sampled from Shed A was high in ash, an observation later repeated for Shed B. A *post hoc* analysis was done to evaluate the hypothesis that soil from the range area contaminated manure, producing the unexpectedly high ash concentrations. Following local research on soil contamination of manure in cattle feedlots (Pratt et al. 2015), the silica concentrations of feed, manure and soil were used to provide a quantitative estimation of manure contamination by soil (f_{soil}). These calculations were made using a linear mixing model:

$$manure\ silica\ (\%) = soil\ silica\ (\%) \cdot f_{soil} + feed\ silica\ (\%) \cdot (1 - f_{soil}) \qquad \text{Eqn 4}$$

Solving for f_{soil}:

$$f_{soil} = \frac{manure\ silica\ (\%) - feed\ silica\ (\%)}{soil\ silica\ (\%) - feed\ silica\ (\%)} \qquad \text{Eqn 5}$$

Implicit in the model was the assumption that hen, egg and water silica concentrations were immaterial. The mass of soil entering the system was determined from the mass of manure:

$$m_{soil} = f_{soil} \cdot m_{manure\ recovered} \qquad \text{Eqn 6}$$

This required a revision of the mass balance equation (e.g. Eqn 2) to include soil as an input to the system. Continuing the phosphorous example:

$$\mathrm{P}_{predicted\ excretion} = \mathrm{P}_{feed} + \mathrm{P}_{water} + \mathrm{P}_{hen\ LWin} + \mathrm{P}_{soil} - \mathrm{P}_{eggs} - \mathrm{P}_{hen\ LWout} \qquad \text{Eqn 7}$$

The concentration of compounds in soil for the respective sheds were obtained from the 0–30 cm soil samples obtained at the experiment outset (Section 2.5).

2.11 Remote monitoring of range

The range area of both sheds was monitored using an outdoor camera (Swift ENDURO 3G model, Outdoor Cameras Australia) mounted on or near the shed, and powered by a solar panel and rechargeable batteries (Swift 3C model, Outdoor Cameras Australia).

Following previous research showing weather and time of day were correlated with ranging behaviour (Hegelund et al. 2005; Gilani et al. 2014), weather data were used to sub-sample the camera records to convert camera observations into qualitative data. For both sheds, minimum and maximum daily temperature were highly correlated, as were daily maximum temperature and radiation ($r^2 > 0.5$, results not shown). We therefore chose a set of days ($n > 20$ per weather parameter per shed) with the daily minimum temperature, and another set with the daily radiation, close to their respective production cycle medians to represent typical days from which to draw observations. Observations at 15:00 hours were targeted (i.e. approximately halfway through pop hole opening hours). For each image, hen range occupation image was classified as vacant (i.e. < 5 hens), hens mostly under shade (i.e. shade of trees and portable shade structures), foraging in the foreground, numerous but evenly dispersed, or a portion thereof (in 0.25 fraction increments).

3 Results

3.1 Productivity and weather data

Key productivity data for free range Sheds A and B are provided below (Table 3-1). The feed conversion rate was higher for Shed A, the mortality rate was greater in Shed A, hen weight at 70 weeks was 5.8% higher in Shed A, and egg weight was higher in Shed B. Rates of feed and water consumption were similar between the sheds. The weather data (Table 3-2) show production took place across a set of seasons that bracketed the long-term observations, although rainfall was about 40% lower than expected.

Table 3-1 Key productivity data for free range egg production facilities

Parameter (unit)	Shed A	Shed B
Feed conversion rate (g feed/g eggs)	2.8	2.2
Feed consumption (g/bird/day)	114	116
Water consumption (mL/bird/day)	172	176
Mortality (%)	12.0	5.5
Flock age at depopulation (wk)	83	76
Hen weight at 20 weeks (g)	1820	1743
Hen weight at 70 weeks (g)	2017	1900
Egg weight (g, 90th percentile)	55.6	62.9

Table 3-2 Weather data for the production cycle of Sheds A and B and the long-term (10 year) observation

Parameter (unit)	Shed A	Shed B	Long-term
Median minimum daily temperature (°C)	15.0	10.8	12.8
Median maximum daily temperature (°C)	29.1	27.2	26.6
Median daily radiation (MJ m^{-2})	19.6	17.7	18.6
Production cycle rainfall (mm)	449	396	-
Average annual rainfall (mm)	-	-	595

3.2 Soil nutrients

The soil nutrient data obtained at the start of the trial at depths of 0–30 cm and 60–90 cm are shown in Table 3-3. All analytes (phosphorous, soluble potassium, nitrate nitrogen and organic matter) were concentrated in the top 0–30 cm. Phosphorous and potassium were present in higher concentrations closer to the shed, especially in the top 0–30 cm. Nitrate and organic matter concentrations showed inconsistent, often unchanging, relationships with distance from the shed.

Table 3-3 Phosphorous, soluble potassium, organic matter and nitrate nitrogen concentrations of range soils at varying distances from the shed and depth (mean ± 1 SD, *n* = 2)

Depth	Analyte (unit)	Shed A						Shed B					
		8 m from shed			18 m from shed			8 m from shed			18 m from shed		
0 - 30 cm	Phosphorous (mg/kg P)	269	±	209	13	±	4	33	±	36	16	±	18
	Potassium, exchangeable (mg/kg)	662	±	192	110	±	79	167	±	80	125	±	0
	Organic matter (%)	2.4	±	0.5	2.3	±	0.4	1.0	±	0.1	1.5	±	0.2
	Nitrate nitrogen (mg/kg N)	50	±	1	74	±	55	52	±	47	47	±	7
60 - 90 cm	Phosphorous (mg/kg P)	7	±	5	3	±	1	3	±	2	2	±	2
	Potassium, exchangeable (mg/kg)	96	±	33	64	±	15	105	±	0	97	±	9
	Organic matter (%)	0.6	±	0.0	0.8	±	0.1	0.6	±	0.3	0.6	±	0.3
	Nitrate nitrogen (mg/kg N)	19	±	19	10	±	0.4	17	±	4	16	±	13

3.3 Water composition

Results from water samples obtained from both sheds (Table 3-4) were within water quality thresholds (Hy-Line International 2018).

Table 3-4 Phosphorous, potassium, nitrogen and total dissolved solids concentrations in water sampled from each shed

Analyte (mg/L)	Shed A	Shed B
Phosphorous	0.03	0.03
Potassium	4	2.3
Nitrate nitrogen[1]	0.61	0.61
Total dissolved solids	736	611

[1] Ammonia and nitrite concentrations were below detection limits.

3.4 Feed composition

The consumption-weighted mean composition of feed for both free range sheds is presented in Table 3-5. The phosphorous and potassium concentrations were similar to each other and between both sheds. The nitrogen concentration was 2.8%, ash concentrations were 13–14%, and volatile solids comprised about three-quarters of the feed consumed.

Table 3-5 Phosphorous, potassium, ash, nitrogen and volatile solids concentration of feed (as fed, consumption-weighted mean)

Analyte	Mean ± one standard deviation (%)					
	Shed A			Shed B		
Phosphorous	0.52	±	0.04	0.48	±	0.04
Potassium	0.58	±	0.02	0.55	±	0.02
Ash	13.8	±	2.3	12.7	±	2.2
Nitrogen	2.8	±	0.1	2.8	±	0.1
Volatile solids	76.4	±	1.2	77.5	±	1.3

3.5 Manure composition

The mean composition of manure for both free range sheds is presented in Table 3-6. Potassium and phosphorous concentrations were similar, but slightly higher for manure from Shed A than B. Similarly, the nitrogen and volatile solids concentrations were higher for manure from Shed A. The manure ash concentration was approximately 50% for both sheds.

Table 3-6 Phosphorous, potassium, ash, nitrogen and volatile solids concentration of manure (fresh weight basis)

Analyte	Mean ± one standard deviation (%)					
	Shed A			Shed B		
Phosphorous	1.56	±	0.2	1.10	±	0.1
Potassium	1.76	±	0.2	1.40	±	0.3
Ash	50.1	±	1.4	49.7	±	0.8
Nitrogen	3.6	±	0.4	2.5	±	0.3
Volatile solids	37.4	±	1.3	27.1	±	2.6

3.6 Egg composition

The egg composition data (Table 3-7) were measured separately for the shell and content to account for the variable material types in each. Residual nutrients in the shell component were associated with the membrane that lined the shell, which was not removed prior to analysis.

Table 3-7 Composition of eggs (*n* = 3, fresh weight basis)

Component	Eggshell (%, mean ± standard deviation)			Egg contents (%, mean ± standard deviation)		
Fraction of total mass	13.6	±	0.4	86.4	±	0.4
Dry matter	75.6	±	1.2	23.3	±	1.8
Phosphorous	0.07	±	0.02	0.11	±	0.08
Potassium	0.06	±	0.004	0.12	±	0.004
Nitrogen	1.1	±	0.1	9.3	±	0.7
Ash	71.4	±	1.1	1.0	±	0.1
Volatile solids	4.3	±	1.6	22.3	±	1.8

3.7 Carcase composition

Layer hen carcase composition (Table 3-8) was relatively enriched in volatile solids and ash.

Table 3-8 Composition of hen layer carcases (liveweight basis)

Component	Mean ± standard deviation[1] (%)
Phosphorous	0.46 ± 0.04
Potassium	0.26 ± 0.04[2]
Nitrogen	2.20 ± 0.1
Ash	8.0 ± 0.2
Volatile solids	26.9 ± 0.2[2]

[1] Uncertainty from Webster et al. (1998).
[2] Assumed to be the same as the analyte above.

3.8 Silica concentration in feed, manure and soil

The *post hoc* analysis of the total silica concentration in a sample of feed, manure and soil (all obtained at the depopulation of Shed B) are shown in Table 3-9. Using Eqn 5, f_{soil} was estimated to be 30.9%. This equated to and 126 and 151 t of soil for Sheds A and B, respectively, which were equivalent to mean rates of approximately 2.1 and 2.5 t soil per week, or 11.8 and 13.7 g/hen/day.

Table 3-9 Total silica concentration in a sample of feed, manure and soil

	Sample type		
	Feed	Manure	Soil
Concentration (%, DW)	1.6	28.1	87.4

3.9 Mass balance

The mass balance results are presented separately for Sheds A (Table 3-10) and B (Table 3-11). For both sheds, water analyte contributions were immaterial, and the analyte mass in hens was broadly comparable. The total inputs were dominated by the feed, so the relative proportions of the analytes are comparable to those shown above (Table 3-5). The mass of phosphorous and potassium removed from the system in the form of hens and eggs were similar. The mass of ash and nitrogen removed was ten-times higher in eggs than hens, and about two-times higher in eggs than hens, respectively.

For each analyte, the mass observed in manure ranged from values approximately equal to predicted excretion or were lower, suggesting possibilities ranging from minor to significant deposition on the range area or emission to the atmosphere. For Shed A (Table 3-10), there was no significant difference between inputs and outputs for phosphorous and potassium. That is, for these compounds, the mass deposited on the range was smaller (negative) than the analytical uncertainty in the measurement. The uncertainty associated with these results is particularly useful for defining the likely upper limits of nutrient deposition. For example, for Shed A phosphorous, the upper uncertainty bound suggests deposition of 11.6% (i.e. the mean + SD), which suggests that the rate of deposition on the range was less than this value. For Shed A ash, the inferred deposition rate was 20.6% of excreted manure, which was significantly greater than zero at the ± 1 SD range. For Shed B, the mass of potassium and ash deposited on the range was not significantly different from zero, but for phosphorous the inferred deposition rate was 10.4% of excreted manure, which was significantly greater than zero at the ± 1 SD range.

When the mean and uncertainty of each analyte-shed combination were used to derive six probability frequency distributions, their summed frequency distribution had a single maximum at 7.2% (Figure 3-1): this point represents the most likely proportion of predicted excretion that is deposited on the range. Because conservative and non-conservative tracers are co-deposited in manure, this deposition rate is applicable to compounds such as nitrogen and volatile solids. Based on these results, 7.2% could be considered a reasonable excretion rate for nutrients from free range sheds.

Table 3-10 Mass balance results for Shed A showing mass of analytes in inputs, outputs, expected excretion and the inferred proportion of excretion deposited on the range

Parameter	Phosphorous	Potassium	Nitrogen	Ash	Volatile solids
			Inputs (kg)		
Feed	7340	8195	39052	193,792	1,076,458
Water	0.1	8.6	1.3	249	1330
Hens	151	86	732	2661	8953
Soil [1]	20	56	124	141,150	3402
Total input (± SD)	7511 ± 529	8345 ± 215	39909 ± 1513	337,851 ± 30205	1,090,143 ± 16041
			Outputs (kg)		
Hens	243	140	1184	4305	14348
Eggs	183	155	10126	38388	25133
Manure, observed	7317	8253	17005	234,478	175,040
Total output	7743 ± 916	8548 ± 708	28315 ± 1929	277,171 ± 5762	214,521 ± 6088
			Mass balance		
Predicted excretion (kg)	7086 ± 530	8050 ± 215	28599 ± 1817	295,158 ± 30209	1,050,661 ± 16302
Mass deposited on range and/or lost to atmosphere (kg)	-231 ± 1058	-203 ± 740	11595 ± 2452	60680 ± 30750	875,622 ± 17158
Fraction of predicted excretion deposited on range and/or loss to atmosphere (%)	-3.3 ± 14.9	-2.5 ± 9.2	40.5 ± 9	20.6 ± 10.6	83.3 ± 2.1

Results are means and uncertainty terms (for brevity, shown for totals only) are ± one standard deviation.

[1] Unlike the other inputs and outputs, soil was not an original component of the mass balance equation (Eqn 2). It was included as an input (Eqn 7) after *post hoc* analyses showed Shed B manure had an unexpectedly high silica concentration. While we are confident the soil input inferred from the silica analyses is representative, it is prudent to point out that the analyses were not replicated, the silica concentration of feed was not assayed over time, and a similar set of measurements was not obtained on samples from Shed A – f_{soil} was extrapolated from Shed B.

Table 3-11 Mass balance results for Shed B showing mass of analytes in inputs, outputs, expected excretion and the inferred proportion of excretion deposited on the range

Parameter	Phosphorous	Potassium	Nitrogen	Ash	Volatile solids
			Inputs (kg)		
Feed	6272	7178	35955	165,258	1,005,010
Water	0.1	4.5	1.2	201	1004
Hens	178	102	859	3124	10513
Soil [1]	4	17	69	149,138	1880
Total input	6454 ± 504	7302 ± 211	36885 ± 1552	317,721 ± 28716	1,018,407 ± 16500
			Outputs (kg)		
Hens	234	134	1132	4118	13856
Eggs	217	184	11982	45424	29740
Manure, observed (kg)	5379	6829	12224	242,848	132,344
Total output	5830 ± 261	7147 ± 1377	25338 ± 1913	292,390 ± 4168	175,940 ± 23248
			Mass balance		
Predicted excretion (kg)	6003 ± 505	6984 ± 211	23770 ± 1978	268,179 ± 28767	974,811 ± 16881
Mass deposited on range and/or lost to atmosphere (kg)	624 ± 567	155 ± 1393	11546 ± 2463	25331 ± 29017	842,467 ± 28508
Fraction of predicted excretion deposited on range and/or loss to atmosphere (%)	10.4 ± 9.5	2.2 ± 19.9	48.6 ± 11.1	9.4 ± 10.9	86.4 ± 3.3

Results are means and uncertainty terms (for brevity, shown for totals only) are ± one standard deviation.

[1] Unlike the other inputs and outputs, soil was not an original component of the mass balance equation (Eqn 2). It was included as an input (Eqn 7) after *post hoc* analyses showed Shed B manure had an unexpectedly high silica concentration. While we are confident the soil input inferred from the silica analyses is representative, it is prudent to point out that the analyses were not replicated, and the silica concentration of feed was not assayed over time.

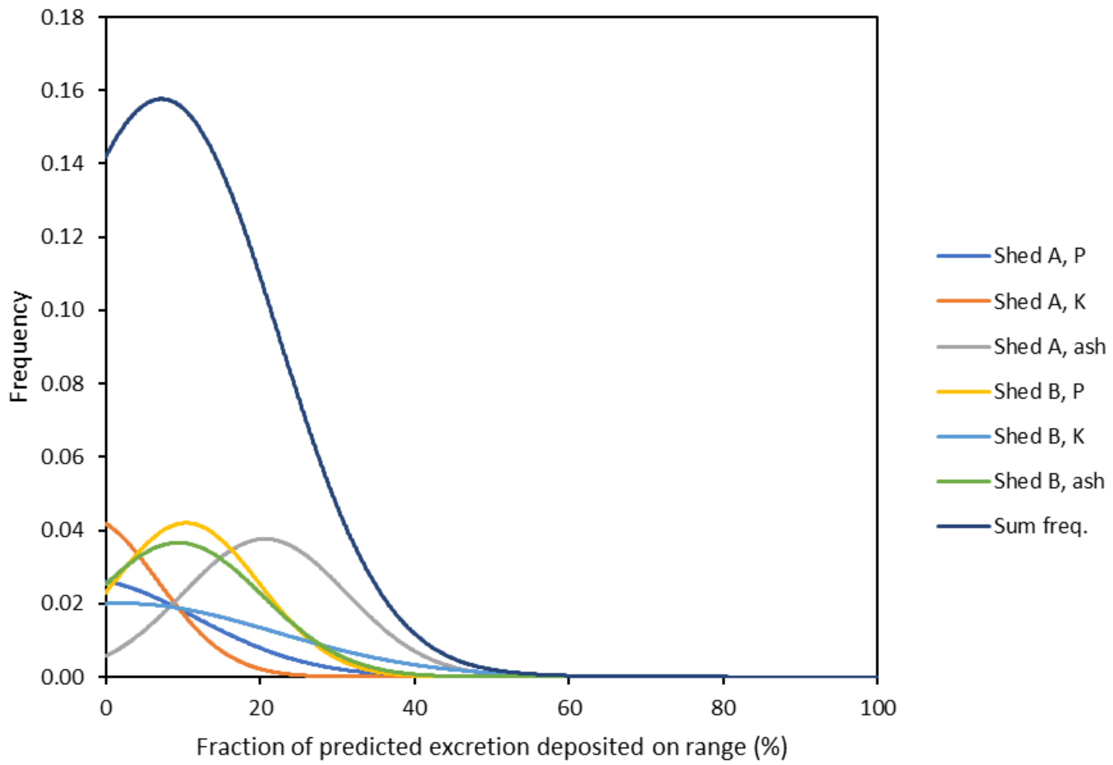

Figure 3-1 The frequency distribution of the fraction of predicted excretion deposited on the range for conservative analytes (phosphorous: P, potassium: K, and ash) from Sheds A and B, and their sum

3.10 Images of the range

Photographs were taken of the range area of Shed B at clean-out, on the day of manure sampling. Excavated hollows were observed in the inner range area, along perimeter fences (Figure 3-2) and in the outer range area (Figure 3-3). These hollows were not observed beyond an exclusion fence in the inner range area.

Figure 3-2 Inner range area of Shed B at clean out, showing hollows excavated by hens along boundary fence

Figure 3-3 Outer range area of Shed B at clean out, beyond the manure pile, showing hollows excavated by hens

A 10 L plastic bucket in the centre of the image provides scale.

3.11 Remote range monitoring

The remote camera observations showed that in the mid-afternoon, the northern inner range area of Shed A was almost exclusively occupied by birds occupying shade (Figure 3-4, top): of > 40 observations in the sub-sampled images, only one showed a fraction of the hens dispersed beyond the shade.

For the northern inner range area of Shed B (Figure 3-4, bottom), 78% of the mid-afternoon remote camera observations showed hens mostly under shade, 15% of observations showed many hens evenly dispersed, only two observations were vacant, and the residual observations (2%) showed a fraction of the hens foraging in the foreground (i.e. near the shed).

Consistent with previous research (Nagle & Glatz 2012; Gilani et al. 2014; Nicol et al. 2003), both sheds showed hens making abundant use of available shade. The more dispersed ranging behaviour for Shed B may relate to the cooler weather (Δ = 4.2°C and 2°C for median daily minimum and maximum temperatures, respectively) (Hegelund et al. 2005). The median minimum temperature and median daily radiation for the Sheds A and B bracketed the same parameters for the long-term (10 year) observations at the weather station from which the observations were obtained (Table 3-2). This increases the likelihood that the overall research findings took place in an environment representative of local conditions.

Figure 3-4 Remote camera images the inner range area showing hen ranging behaviour for Shed A (top) and Shed B (bottom) at a flock age of 50 and 52 weeks, respectively

Portable shade structures and native trees can be seen in the middle and backgrounds of both images.

4 Discussion

4.1 Manure composition

The concentration and mass of ash in the manure was high

The ash concentration of manure (and other biosolids) is commonly inferred from the ratio of volatile solids (VS) to total solids (TS) based on the following relationship:

$$total\ solids_m = volatile\ solids_m + ash_m \qquad \text{Eqn 8}$$

where the subscript *m* indicates mass. So, a sample with a low VS/TS ratio is relatively high in ash. The *Egg Industry Environmental Guidelines* (McGahan et al. 2018) indicate typical VS/TS ratios for fresh manure are in the range 61–84%, which is comparable to the range observed for chicken manure in the *Phyllis* biomass feedstock database (https://phyllis.nl/) (58–86%, n = 12). The VS/TS ratio for Sheds A and B were 43 and 35%, and thus much lower than typically observed, indicating an unexpectedly high manure ash concentration.

One possible explanation for the contrast is decomposition of the Shed A and B manure samples over the course of the 60+ week production cycle. The loss of volatile solids would drive the VS/TS ratio lower. However, this idea was not supported when compared to first principles analysis. Manure deposition (i.e. TS) can be estimated by multiplying 1-DMD (Khempaka et al. 2018) by total feed consumed across the production cycle (corrected for moisture content), and multiplying this by typical VS/TS ratios. For Shed B, this check produced an estimated manure ash mass of 48–143 t, which was 100–195 t lower than observed (Table 3-11). There was therefore a sound rationale for exploring sources capable of elevating the ash concentration and mass of manure recovered from the free range sheds.

Silica analyses showed contamination of manure with soil

The preliminary set of silica analyses showed approximately 30% of the manure in Shed B was soil. This was equivalent to transporting several tonnes of soil into the shed per week. In terms of the mass balance experiment, failure to account for the contamination of manure by soil was important to the ash results only (changes for the other analytes were within the analytical uncertainty). This was because the soil was enriched in silica and relatively depleted in the other analytes (Table 3-11). However, the soil nutrient analyses came from the 0–30 cm depth interval, and it is possible that the nutrient concentrations for this interval were not representative of the soil surface (i.e. < 3 cm depth), particularly for phosphorous. Previous research has shown phosphorous can be highly concentrated in the top 10 cm of soil, especially where nutrient depositions rates are high (Gale et al. 2000). The transport of soil with elevated phosphorous concentrations to the manure in the shed would have a slight impact on the phosphorous mass balance result – for Shed B, a five-times increase in soil concentration would increase the fraction of predicted excretion deposited on the range by 1%.

The mode of soil transport into the shed is unclear

Identifying the mode/s by which soil was transported into the free range egg production sheds is unclear – the most likely explanations were: (1) geophagy (i.e. the ingestion of soil by hens); and (2) soil adhering to the body (e.g. feathers); or (3) the feet of hens. The plausibility of each of these mechanisms is examined below.

For Shed B, the contamination of shed manure by soil was equivalent to soil consumption at a rate of 14.5 g/hen/day. This would be equivalent to 11.1% of daily total consumption (i.e. soil plus feed) (Table 3-1). Applying the Shed B estimate of manure soil contamination (f_{soil}) to Shed A suggested soil contamination equivalent to 10.2% of daily total consumption. There is a paucity of information in the peer-reviewed literature against which these estimates can be compared (Jurjanz et al. 2015). A French study of free range layers reported soil consumption of 3.6 to 7.2 g soil/day on a complete layer diet, and soil consumption as high as 15 to 30 g soil/day on a whole wheat (plus shell grit) diet (Jondreville et al. 2010). Another French study showed free range broilers generally consumed < 3 g soil/day but could reach as high as 5 g soil/day, with older birds ingesting more soil than younger ones, and birds on tree-covered ranges consuming more soil than those on grass-covered ranges (Jurjanz et al. 2015). In the latter study, both range types had complete cover at the start of the experiment but were both denuded (especially the tree cover treatment) by the experiment close. It is possible to estimate the percent soil consumption using a soil-ingestion equation developed for wildlife (Beyer et al. 1994). Using dry matter digestibility from the literature (Khempaka et al. 2018) and observed ash contents in Shed B manure, feed and soil (i.e. 1 – fraction of organic matter), the soil-ingestion equation predicted 5.9% soil in the diet (feed plus soil). However, the soil-ingestion is highly sensitive to assumed dry matter digestibility – changes of ± 5% yielded solutions ranging from 1.2 to 10.2%. From these comparisons it is concluded that the estimated soil consumption rates are plausible, especially given (1) the variability observed in the cited reports; and (2) the possibility that soil consumption is higher in denuded range areas like those of Sheds A and B.

An alternative mechanism for the transport of soil into a shed was via the body of hens returning to the shed from the range area. If it is assumed the surface area of the ISA Browns in Shed B could be approximated by a 25 cm diameter sphere, the inferred contamination of the manure by soil would be equivalent to the average daily removal of 28 mg of soil from every square centimetre of each bird. This is difficult to visualise but would be equivalent to above one-tenth of a pinch of salt (Winkler et al. 2012). The rate of soil introduction is approximately 30 to 300 times greater than the dust level that may be expected in a poultry house (Wathes et al. 1997). This mechanism of transport could be expected where hens make abundant use of dust baths such as hollows (Figure 3-2 and Figure 3-3), then carry the dust into a shed on their plumage.

Another possible mode of transporting soil into a free range shed would be soil concentrated on the feet of hens, for example if the birds walked or stood in mud. The effectiveness and likelihood of this mode of transport is reduced by the presence of the concrete-skirting around the shed, and the gridded ramp the hens must walk up to re-enter a pop hole, both of which would remove at least some soil from the feet of hens. The nearby weather station showed 9% of days in the production cycle of both Sheds A and B registered ≥ 3 mm of rainfall, which indicates the possible presence, albeit infrequent, of muddy surfaces.

The present study was unable to identify the source of soil contamination, and further research is warranted to examine this. In particular, determining contamination via consumption may be important from a bird health and nutrition perspective, and an indication of this could be derived from free range sheds that utilise manure belts, which could be expected to have less contamination from dust or soil from the birds' feet.

High rates of geophagy may have negative effects on egg production

As explained in Section 4.1, one possible explanation for the high silica content of shed manure was geophagy. High rates of soil consumption by birds was not confirmed, so identifying the possible implications of geophagy will be kept brief. High rates of sand consumption (up to 30%) over four weeks showed no effect on productivity (egg production or weight) but a decrease in body weight gain (van der Meulen et al. 2008). This is consistent with research on the effect of diet dilution (van Krimpen et al. 2009). In the present research, bird weights (data not shown) were in the upper percentiles expected of growing birds (Hy-Line International 2018), so geophagy-induced reductions in growth were highly unlikely. The consumption of soil by layer hens is a concern in sites with contaminated soil – toxic compounds such as dioxins and lead can be transferred to eggs (Waegeneers et al. 2009; De Vries et al. 2006). Thus, the transfer of toxins to eggs via geophagy will be related to site history. Because geophagy may have implications for bird health, productivity and food safety, precautionary practices should be used when establishing new free range farms, particularly on the site of an existing farm or other industry. For example, the historic use of organochlorines on farms is an ongoing concern in Australia (DPIRD 2020; Agriculture Victoria 2020). A risk assessment should be conducted to determine the likelihood and impact of previous site use on the proposed farm, perhaps informed by soil tests for chemical or heavy metal contamination.

High ash concentrations de-value manure as a co-product of free range egg production

Layer hen manure is a valuable co-product of the egg production system, but its value is potentially reduced by high concentrations of ash. The long production cycle contributed to the low VS/TS of manure in the present research, which can be an advantage for manure as a fertiliser source because it reduces the material bulk and concentrates nutrients such as phosphorus. However, there was also evidence of significant amounts of soil being introduced into the manure. This had the effect of diluting the nutrient value of the manure and increasing handling costs to utilise this material as a fertiliser. Similarly, high ash levels are disadvantageous when manure is used as a substrate for biogas production. In the latter case, the yield of biogas per mass of manure would decrease, and the costs of removing waste would increase.

4.2 Range Management

The volume of nutrients deposited on range areas is small but associated with large uncertainty

In the present research, results for conservative compounds showed the most likely rate of manure deposition in range areas was 7.2% of predicted excretion (Figure 3-1). This is consistent with international research that shows the proportion of predicted excretion deposited in the range area can vary widely, from a few percent up to 45% (Table 4-1). Previous observations of the phosphorous deposition rate in range areas were similarly variable, ranging from 0.02 to 0.66 g/hen/day. The phosphorous deposition rates for Sheds A and B were at the lower end of this observed range, as were the proportions of predicted excretion deposited on the range (Table 4-1). These observations hold true even when the analytical uncertainty in the present estimates is considered.

Table 4-1 Reports of nitrogen and phosphorous deposition in free range areas as rates and as a proportion of total manure deposition

Reference	Country	System, product	Nitrogen (g/hen/day)	Phosphorous (g/hen/day)	Excretion on range (% predicted)	Comment
Dekker et al. (2012)	Netherlands	Organic free range egg,	2.4	0.54	2	Farm 1
			2.7	0.62	17	Farm 2
			2.9	0.66	8	Farm 3
Aarnink et al. (2006)	Netherlands (inferred)	Free range, egg			45	First 20 m of run
		Floor housing, egg			33	First 20 m of run
		Aviary housing, egg			20	First 20 m of run
Meda et al. (2015)	France	Organic free range, broiler	0.1	0.02	2	Winter-spring, tree
			0.5	0.13	20	Winter-spring, grass
		Organic free range, broiler	1.1	0.31	44	Summer-autumn, tree
			1.0	0.27	38	Summer-autumn, grass
Wiedemann et al. (2018 and references therein)	Australia	Free range, egg	0.2	0.08	14	
Present report	Australia	Free range, egg	-	0 [a]	0 [a]	Shed A
			-	0.06	10	Shed B

[a] Negative rates for Shed A were implausible and therefore rounded up to zero.

Manure excretion in the range area may be influenced by bird behaviour. Predicting or quantifying ranging behaviour is challenging because it is a function of complex genotype × environment × management interactions. The relevance of the present research to other sites will depend on contrasts in attributes such as flock size, season/weather, early outdoor rearing experience, flock age, pop hole availability, shed light intensity, hen health, and the availability of shade (artificial or otherwise) (Chielo et al. 2016, and references therein).

The relevance of the deposition rates in the range area observed in the present research in other contexts is a function of both ranging behaviour and the metabolic routing of nutrients. Given macronutrients are an important determinant of productivity and hen health, commercial layer diets are expected to have optimised nutrient composition and availability – sub-optimum diets are unlikely, but supra-optimum diets (which would increase nutrient excretion rates) may be possible. The latter would elevate deposition rates in the range area.

Having noted this, the results found for Shed B in the present study indicate it is most likely ≤ 10% of phosphorus (and by extension, nitrogen) can be expected to be excreted in the range area. This concords with soil nutrient distribution in previous research (Wiedemann et al. 2018), which indicated soil phosphorous levels trend towards background levels within a short distance of a free range shed, indicating relatively modest phosphorous excretion rates in the range relative to total excretion from the birds. This is consistent with research on ranging behaviour on Victorian free range farms that shows the duration hens spent on the range varied widely, with a median in the range of 14–16% (Larsen et al. 2017). The implication is that the present and past research points towards significant (i.e. greater the zero) but not large (i.e. < 20% of predicted excretion) masses of nutrients deposited in range areas. This supports the continued application of current industry recommendations for managing nutrients in free range areas (McGahan et al. 2018).

Range management implications of high concentrations of soil in shed manure

Regardless of the mechanism responsible for transporting soil into the free range sheds in this study, the results point to the possible ongoing removal of soil from the range area. With some reasonable assumptions (hens occupy a shed for 60 weeks, there are two weeks between flocks, soil has a bulk density of 1.2–1.4 g/cm^3, and all soil was sourced from the inner range, which at this farm was 0.75 ha), the soil removal for Shed B would be equivalent to soil removal of 120–140 mm over 10 years. Even if this is considered an upper estimate (e.g. if soil contamination was particularly high during the study period, which aligned with historic drought conditions), this rate of soil removal would make it highly likely that there are holes forming in the range area (e.g. Figure 3-2, Figure 3-3) that would require rehabilitation. Testing shed manure for silica would provide the most direct assessment of the rate of soil transport into a free range shed. This can be calculated using Eqn 5, and the feed percent silica value presented here for diets that do not contain silica-rich grit (Table 3-9). However, the soil silica content can vary widely: values ranging from 43 to 81% (Pratt et al. 2015) or as high as 87% (Table 3-9) should provide a first-order estimate. For example, at another farm a total silica content of 5.7% was observed in free range manure with a VS/TS ratio of 0.59, both of which would suggest low contamination of manure by soil. This possibility was supported using Eqn. 5 and our feed and soil silica values:

$$f_{soil} = \frac{5.7\% - 1.6\%}{87.4\% - 1.6\%} = 4.8\% \qquad \text{Eqn 9}$$

The estimate for f_{soil} can then be multiplied by an estimate of excretion (e.g. total feed consumption multiplied by 1 – dry matter digestibility, e.g. 1–0.75) to estimate the mass of soil brought into a shed over the course of a production cycle. If a shed housed 20,000 hens over 60 weeks and each hen consumed 110 g of feed per day:

$$110 \text{ g feed/hen/day} * 20{,}000 \text{ hens} * 420 \text{ days} * (1 - 0.75) * 4.8\% \div 1000000 = 11 \text{ t} \qquad \text{Eqn 10}$$

In this worked example, the mass of soil brought into the shed would double if the soil silica content were as low as 43%.

While further research is required around the implications of soil contamination on range management, bird health and food safety threats, this possibility should be considered in future updates of the environmental guidelines and risk assessment for range areas.

4.3 Limitations

Analytical uncertainty in system inputs and outputs

The two major sources of uncertainty in the present research were manure and feed composition. This was because these sample types were the largest fluxes in the system (ahead of eggs). The analytical uncertainty of manure analyses was typically slightly larger than that of feed analyses, except for ash (coefficient of variation of 17.4 and < 3%, respectively). The analytical uncertainty of these sample types will be prone to outliers because of their heterogenous composition – ensuring samples are representative and increasing the number of replicates are both effective at addressing this source of uncertainty. However, the latter is the more difficult strategy to employ over long observation periods (such as those of the present research) because it increases analytical costs.

Uncertainty in silica concentrations

The *post hoc* silica concentrations were incomplete relative to the input and output masses and concentration data that formed the basis of the original mass balance approach (Eqn 2). The percent silica was based on a single set of feed, manure and soil measurements obtained at the end of the Shed B production cycle (as explained in Sections 2.10 and 3.8). Consequently, there was no analytical uncertainty associated with these measurements. Only trace amounts of silica were expected in cereal grains (Lanning & Eleuterius 1992) and the grit was limestone – this was consistent with the very low silica concentration observed in feed (Table 3-9). Silica was a considerable proportion of the manure (Table 3-9), which was expected given the high manure ash concentrations. Previous research has shown soil on the Darling Downs is rich in silicon (Pratt et al. 2015), increasing confidence in our soil silica measurement. The contrast between the soil and feed silica concentrations maximised the resolving power of silica as a tracer for the presence of soil in manure. Thus, despite the lack of replicates, there are multiple reasons to be confident that the silica results were representative. We are confident there is greater merit incorporating the silica concentration data and the inferred soil input into the mass balance calculations, than omitting these sources of information.

Type of free range system studied and environmental conditions

The rate of nutrient excretion in the range area is a function of hen ranging behaviour, and the amount of nutrient excreted per unit area is a function of hen density. Accordingly, the results of this study will be of greatest relevance to similar systems with similar management (i.e. free range, fixed sheds, relatively high stocking rates per hectare), environments (i.e. low percentage of ground cover in the inner range area, sub-tropical climate, moderate, summer-dominant rainfall), and hens (i.e. layers). For example, management consisting of smaller sheds, lower stocking densities, portable sheds, or environments with a more positive water flux (e.g. wetter seasons), could demonstrate different characteristics in terms of ranging behaviour and potentially levels of soil contamination (soil transport into the shed via ingestion, dust bathing and on feet). This could produce a contrasting rate of excretion on the range as well as shed manure with a contrasting composition. An industry survey of the chemical composition of manure in free range sheds, annotated with relevant contextual information, would be a straightforward means of identifying management × environment interactions with high manure ash contents, with the added benefit of placing the current research in context.

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6 Plain English Summary

Project Title:	Determining manure deposition in free range sheds and free range areas
Australian Eggs Limited Project No	1RS904IA
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Objectives	To determine manure nutrient excretion in a free range shed via mass balance.
Background	It is not known what proportion of the nutrients in manure are deposited inside and outside a free range shed, making estimation of nutrient deposition uncertain.
Research	The mass balance approach was used to quantify inflows (e.g. feed, water, hens) and outflows (e.g. eggs, hens, shed manure) to/from two commercial free range sheds. The difference between these flows represents mass lost from the system – either as an emission to the atmosphere, or as manure deposited on the range.
Outcomes	The most conservative interpretation of the mass balance experiment was that outside excretion was less than 20% of total excretion, and the most likely proportion was 7.2%. While these results are of greatest relevance to similar farms (i.e. fixed sheds, outdoor population densities < 7300 hens/ha), they were consistent with literature on hen behaviour and international research on nutrient deposition rates in range areas. Consequently, these results are recommended for use in predicting excretion rates in the range areas of new and existing farms. High concentrations of ash in the manure of the free range sheds studied was unprecedented. Further research is recommended to understand how widespread this phenomenon is, the mechanism/s responsible for the ash accumulation, and implications of this on food safety, bird health, productivity and environmental management of range areas.
Implications	Nutrient deposition in the range area is influenced by multiple variables, including feed composition, but especially ranging behaviour. The present findings are highly relevant to the farm studied, and will be indicative for industry more broadly. The results confirmed that although significant (i.e. greater than zero), the mass of nutrients excreted in range area was minor (< 20% of total nutrients in excretions). This supports the continued use of current industry practices for managing nutrients in range areas. The silica concentration in manure is evidence of soil transport into free range sheds. Extrapolating over ten years, this would be equivalent to soil

	removal in the inner range area of up to 140 mm. Holes were observed in the range area, suggesting these may be symptomatic of soil export from the range area. Maintaining groundcover should reduce soil export, and high concentrations of (total) silica in manure is a reliable indicator of contamination. Considering the potential of these results to indicate reasonably high levels of soil consumption by free range hens, a precautionary approach to managing risks from soil contamination is recommended for new and existing free range sites. We recommend conducting a risk assessment to assess the risk of potentially hazardous materials in range area soils, to avoid the potential for negative bird health and food safety outcomes. The (1) proportion of excreted nutrients deposited on the range areas and (2) the possible implications of shed manure contaminated with soil on range management, bird health and food safety threats, should be included in future updates of the environmental guidelines and risk assessment for range areas.
Key Words	Free range, manure, nitrogen, phosphorous, ash
Publications	None