Final report

Finishing lambs: optimising preparation and adaptation of lambs to improve finishing performance

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Abstract

This MLA Donor Company funded project with research conducted by Charles Sturt University aimed to collate the state of knowledge regarding lamb growth rates and identify constraints on individual lamb performance in feedlots. The key constraints on lamb growth rates were identified from a literature review and a series of experiments investigated growth rates and body composition of lambs under different nutritional and stage of lamb maturity treatments. An experiment to assess the benefits of creep feeding and backgrounding was conducted; however, conclusive results were constrained by the low growth rates observed in a finishing period in the feedlot. Subsequent experiments sought to focus on the constraints in the feedlot.

The second experiment investigated the impact of feeding level and stage of maturity on growth rate, body composition and diet digestibility in a cohort of lambs. A third experiment investigated the effects of feeding lambs a pelleted diet with the fibre component incorporated compared to a pelleted diet with roughage fed separately on lamb growth and body composition. A separate cohort that grazed lucerne was included to compare the compositional changes between confinement fed and pasture fed lambs. Finally, modelling of lamb growth and body composition was conducted using body compositional data generated from CT scans in the second experiment. This compared the prediction accuracy of two published models with alternative methods for the estimation of heat production energy losses with the aim of supporting the development of a calculator that better reflects the realities of lamb growth by accounting for nutritional history and stage of maturity.

The results generated from this study indicate that providing lambs with a feedlot ration prior to feedlot entry may be a technique to increase feed intake and growth rates in the feedlot but more research is required to confirm this finding. Lambs fed high concentrate diets and in confinement, deposit a greater amount of empty body fat and decreased lean tissue in comparison to animals grazing pasture. The commonly reported phenomenon of compensatory growth was not observed in the current research, highlighting the importance of accurately predicting heat production energy costs to better predict growth responses. CT scanning of lambs demonstrated the technology's advantages as a non-destructive method for repeated measures of body compositional changes in growing lambs.

Executive summary

Background

Lamb feedlotting is becoming an important component of lamb production systems in Australia, providing insurance against annual and seasonal variations in feed supply. Intensively feeding lambs through the unrestricted provision of high quality nutrients should, in theory, result in lambs achieving their genetic potential for growth. Lamb growth rates in feedlots are highly variable and often well below expectations and the most likely limitation is the insufficient intake of nutrients to enable maximal growth. The primary question this research proposed to answer was whether nutrient intake was the predominant constraint on lamb growth and what other constraints exist when lambs are intensively fed. It was hypothesised that alternative management of the adaptation period prior to lamb feedlot entry might increase subsequent nutrient intake.

This research was targeted at lamb producers intensively feeding lambs and particularly those that have invested in high growth genotype lambs. This research has enabled the improved understanding of growth rate observations for researchers and commercial sheep producers alike and will contribute to the more precise predictions of lamb growth rate and feed conversion ratios. Further targeted investigations will enable the refinement of a predictive growth modelling tool which will enable producers to better estimate the costs of feeding and calculate indicative returns prior to the commencement of feeding.

Objectives

The project aimed to collate the state of knowledge regarding lamb growth rates and finishing and identify constraints on individual animal performance in lamb feedlots. A literature review collated the state of knowledge regarding lamb growth rates and is included as an Appendix to this report. The key constraints on lamb growth rates were identified from the literature review and a series of experiments investigated energy transactions under varied nutritional management and at different stages of lamb maturity.

The project aimed to improve backgrounding and/or induction/adaption procedures for lambs entering feedlots, identify the cost of shy feeders/non eaters in lamb feedlots and develop best practice management guidelines to improve their health and welfare. An experiment to interrogate creep feeding and backgrounding was conducted; however, conclusive results were constrained by the low intake of supplements pre-weaning (attributed to the sufficient availability of high-quality pasture placing no restrictions on the nutrient intake of lambs or the milk production of ewes) and low growth rates observed in a finishing period in the feedlot. Subsequent experiments sought to focus on the constraints in the feeding period rather than in the preparation of lambs for feedlotting.

A survey of producers identified the key constraints in lamb feedlots and a partner project (P.PSH.1321) is building on these results by conducting a large survey of causes of ill-health and mortality via cohort studies in lamb feedlots in southern Australia; combined these will facilitate production of management guidelines to improve the health and welfare of lambs in feedlots. The cost of shy feeders was not calculated as there was insufficient data to provide an accurate cost; although from the survey it was identified that a median of 3.5% of lambs entering feedlots may be affected.

Results were disseminated through scientific publications, field days and industry forums although it was not possible to hold face to face field days associated with the specific experiments due to logistics and COVID restrictions during the key field research phase of this project (October 2019 to May 2021). Details have been included in the objectives section of this report.

Methodology

The project method had the below components:

a. A literature review collated the state of knowledge regarding lamb growth rates.
b. A survey measured lamb growth rates pre- and post-weaning under commercial conditions to benchmark growth rates.
c. An online survey of producers operating a lamb feedlot was disseminated using a media campaign with local and social media to identify the current state of the lamb feedlot industry and identify possible research questions.
d. A series of three field trials to investigate components identified from the literature review that could be answered using live animals:
    i) An experiment investigated the impact of creep feeding and backgrounding of lambs and weaning direct into a feedlot on lamb performance in the finishing phase
    ii) An experiment investigated the impact of feeding level and stage of maturity on growth rate, fat and protein deposition and diet digestibility in a cohort of lambs
    iii) An experiment that investigated the impact on lamb growth and fat and protein deposition from feeding a pellet with the fibre component incorporated compared to a pellet with roughage fed separately. A separate cohort grazed lucerne in a paddock to provide a feedlot v. pasture comparison.
e. Modelling of lamb growth using CT scan-derived body composition in the second field experiment to make comparisons between two published models.

Results/key findings

Key findings from this project are:

- Nutrient intake is the predominant constraint to maximising lamb growth rates in intensive feeding production systems and improving adaptation to diet and diet composition are key components to improving production.
- Providing lambs with a feedlot ration prior to feedlot entry and the commencement of an induction period may increase feed intake and growth rates in the feedlot following induction, but more research is required to confirm this and the mechanisms responsible.
- The commonly reported phenomenon of compensatory growth (whereby animals previously restricted exhibit faster growth with improved feed conversion ratios to their continuously grown counterparts) was not observed in the current research highlighting the importance of accurately predicting heat production energy costs to better predict growth responses.
- Lambs fed energy dense, grain based diets in outdoor confined bare-earth pens deposit a greater amount of fat and decreased lean tissue in comparison to pasture fed animals.
- CT scanning of lambs demonstrated considerable advantages for assessing treatment impacts on body composition compared with comparative slaughter studies, as it is a non-destructive method for repeated measures of body compositional changes in growing lambs.

Benefits to industry

This report outlines explanations for the variability in lamb growth rates commonly observed in both commercial and research situations. Variations in lamb growth in response to intensively feeding lambs in commercial situations can be explained through an improved understanding of the effects of nutrient supply on gut fill, organ mass and body composition. This report provides a methodology for researchers to conduct experiments to determine treatment effects with greater precision and will hopefully stimulate researchers to not rely solely on animal liveweight to make conclusions. This research clearly identifies opportunities for further research to improve the precision of predictive growth modelling, improvements in which will have a substantial impact on the red meat industry.

Future research and recommendations

Suggestions for future research:

- A longitudinal study over multiple seasons collecting data from a range of feedlots with different feeding systems, diet types, induction protocols and lamb genotypes,
- Assessment of benefits to lamb growth rate and nutrient intake of creep feeding and backgrounding across multiple seasons with recording of individual animal intake and analysis of rumen parameters.
- Research to better understand the effects of pasture characteristics (quality and quantity) on supplement and pasture intake whilst grazing pasture.
- Research that includes recording of individual animal intake and body compositional changes of diverse sheep genotypes (such as Merinos, cross-breds and shedding sheep) in a feedlot environment.
- Experiments feeding a wide range of diets (such as varied grain and forage contents and varied protein and energy supply) and feeding levels to lambs in confinement feeding to further evaluate and develop predictive lamb growth models.
- Assessment of the activity energy costs of grazing, ruminating and walking in sheep grazing pasture to quantify the energy conserved by confining lambs in a feedlot.

Contents

1. Introduction

Maximising lamb growth from weaning to slaughter through improved nutritional management has greater potential to increase the production efficiency of lamb producing farms than the genetic selection for growth (Hegarty et al. 2006). Lamb growth is controlled by the mature weight of an animal and the extent to which environmental constraints, such as nutrition, allow genetic potential to be expressed. The reason that nutrition is likely to be more influential than genetic selection on maximising lamb growth is that, in commercial settings, maximal lamb growth is rarely realised and insufficient nutrient intake appears to be the predominant constraint (Oddy and Walmsley 2013).

A lamb expressing its genetic potential for growth and weaned prior to 16 weeks of age should initially exhibit increased growth rates or, at the very least, have a similar rate of liveweight gain to that observed pre-weaning (Johnson et al. 2012). Prior to weaning, lamb growth rates are usually similar to theoretical unconstrained growth (see Appendix 9.1). Reports of increased growth rates post-weaning are rare and are more likely due to errors in measurement than actual lamb performance (Robinson and Oddy 2001; Oddy and Walmsley 2013).

Lamb growth rates in feedlots are highly variable (ranging from -51 to 409 g/day) but it has been reported that lambs have the genetic capacity to achieve growth rates over 400 g/day (Jolly and Wallace 2007), suggesting many lambs in feedlots are not reaching their potential despite the provision of the unrestricted supply of high quality nutrients. If practical measures capable of increasing nutrient intake were realised, it could be expected that growth rates of lambs fed in feedlots would increase (Oddy and Walmsley 2013).

The questions that evolved to address this issue included:

- Is nutrient intake the major constraint on lamb growth in intensively fed lambs and are there additional constraints within these systems?
- Could nutrient intake be promoted by extending the adaptation period to a high concentrate diet or by better familiarising lambs with the diet?
- Do lambs exposed to a prior nutritional restriction have improved efficiency of empty body gain?
- Do lambs at later stages of maturity have an improved ability to digest feed?
- What is the contribution of the energy costs associated with walking, grazing and moving about in explaining observations that pasture fed sheep are typically leaner than those fed a high-concentrate diet in confinement?
- How accurate is the current approach for the prediction of liveweight gain using nutrient supply and are there alternatives?
- Can CT scans be used for repeat measures of body compositional changes in growing lambs and can this technique therefore be used to test and improve the precision of lamb growth models?

This research was targeted at lamb producers intensively feeding lambs to reach slaughter weights and particularly those that have invested in high growth genotype lambs. The results will be used to inform industry professionals and producers of the expectations for the growth rates of intensively fed lambs and provides explanations for suboptimal performance in these systems. This report outlines opportunities for future research projects to improve the precision of predictive lamb growth modelling which will be of substantial value for commercial producers in the future.

2. Objectives

1. Collated the current state of knowledge regarding lamb growth and finishing via a literature review and identified potential researchable questions.

A literature review was completed and is included as an Appendix to this report. The researchable questions have been listed in the results (Section 4.1).

2. Identify constraints on individual lamb performance in lamb feedlots.

The key constraints on individual performance were identified from the literature review, survey and experimental data. In summary they are:

- The prevalence of shy feeders, which based on the producer survey was a median 3.5% of lambs that enter a feedlot.
- Acidosis is reported to contribute to 50% of lamb mortalities in feedlots. Reported mortality rates are, however, generally low (approximately 1%).
- A clear constraint on the expression of a lamb's genetic growth potential is nutrient intake, and particularly the intake of metabolisable energy, with improvements in diet adaptation and changes to diet composition likely to be beneficial.
- The provision of low quality fibre sources (e.g. straw and poor quality hay), restricts nutrient intake, due to gut fill.
- The low growth rates (< 200 g/day) reported by 16% of lamb feedlot operators reported in the producer survey.

3. Improved backgrounding and/or induction/adaption procedures for lambs entering a lamb feeding system through a series of controlled animal trials.

An attempt was made to complete this objective; however, low intake of supplements (<100 g/head/day) prior to entering a feedlot and low growth rates in the feedlot constrained conclusive results. There was some evidence that increasing the length of exposure to a feedlot ration increased nutrient intake in the feedlot although results were insignificant. This observation is supported by the literature that increased exposure to a high concentrate ration increases nutrient absorption and reduces the effects of an induced ruminal acidosis. While this objective was not specifically met, this research suggests possible avenues to achieve this and outlines approaches to investigate this in greater depth. A partner project (P.PSH.1321) will provide more information on practices associated with backgrounding and induction in commercial feedlots to further inform this discussion.

4. Identified the cost of shy feeders/non-eaters in lamb feedlot operations and develop best practice management guidelines to improve their health and welfare outcomes.
    a. Developed a two page technical note for producers on managing the adaptation phase – in discussion with the MLA Communications Team

It was estimated from the survey that 3.5% of lambs entering feedlots could be considered as shy feeders (the median result reported in the survey). However, there was insufficient data available for an accurate cost of shy feeders to be made, as it could not be determined the proportions of these that are removed from the feedlot and sold, removed and later recover, and are able to be finished on feed or pasture, or that die. Furthermore, the average time that shy feeders were on feed before being identified and removed was not available. There was therefore considerable uncertainty in any calculation of the cost of shy feeders. A partner project (P.PSH.1321) will provide more information on practices associated with induction and treatment of shy feeders in commercial feedlots to better inform this discussion.

The two page technical note has been provided to the MLA Communications team.

5. Published at least one peer reviewed scientific journal article.

One peer reviewed paper has been published in Animal Production Science and a second is currently under review by the Journal of Animal Science. In addition, four conference papers have been published/presented. A full list can be found in Appendix 9.2

6. Completed a minimum of two field days engaging over 100 producers over the life of the project.

Due to restrictions during the period of the project, no field days were held on site. The project team therefore sought alternate forums to engage producers, including:

a) An "Online" Lamb Feedlot Seminar hosted by Charles Sturt university (November 24, 2020). Speakers included Shawn McGrath, Thomas Keogh, Bruce Allworth, Cara Wilson (CSU), Ben Holman and Sabrina Meurs (NSW DPI)
b) MLA productivity and profitability webinar on 'Maximising lamb growth – pre and post weaning' – December 2020. (150 attended, further 350 views online)
c) Sought additional industry forums to present results at (outlined below).

7. Presented project outcomes at a minimum of three industry forums

Research outcomes were presented at several industry forums, many of which were online due to restrictions:

I. 2020 Graham Centre Forum – "Finishing lambs – optimising preparation and adaptation of lambs to increase feed intake and subsequently growth rate" (150 people online)
II. 2021 Australian Association of Animal Sciences (AAAS) - "Nutritional management of lambs prior to feedlot entry can effect feedlot growth rate" (50 people online)
III. 2021 AAAS - "Lamb feedlot cross sectional study: Current practices in the Australian lamb feedlot" (50 people online)
IV. Charles Sturt University Higher Degree by Research symposium - "Understanding the constraints on lamb growth in intensive feeding systems" (30 people online)
V. 2021 Graham Centre Forum – "The effects of feeding level and age on lamb growth rate and feed conversion efficiency" (80 people online)
VI. 2021 Charles Sturt University Lamb Feedlotting seminar - "Current practices in the Australian lamb feedlot" (30 people online)
VII. 2022 British Society of Animal Science – "The effects of feed intake at two stages of maturity on the body composition of cross-bred lambs" (Finalist in presidents prize – 50 people online; and presented in sheep nutrition seminar – 50 people online)

VIII. 2022 Australian Association of Ruminant Nutrition - “Energy transactions in lambs fed differing levels of a pelleted diet at two stages of maturity” (100 people in person)
IX. 2022 AAAS - “Stage of maturity and energy intake level influences protein and fat deposition in cross-bred lambs” (60 people in person)
X. 2022 Henty Machinery Field Days – Gulbali Institute Researcher presentations – Shawn McGrath - “Supplementation and management of sheep for production and growth - Recent findings and current research”
XI. 2021 Merino Link conference – June 2021

3. Methodology

3.1 Literature review

A literature review (Appendix 9.1) was conducted to collate the current state of knowledge regarding lamb growth and finishing lambs in intensive feeding systems. The literature review:

- Investigated lamb growth rates and made comparisons to expected genetic potential
- Collated information on the management of the weaning transition and rumen development
- Identified potential constraints on lamb growth rate and opportunities to mitigate these effects
- Reviewed recommendations for adaptation to feedlots and high concentrate diets
- Outlined the effects of genetic selection in terminal sires
- Described the impacts of nutrition on the composition of liveweight gain and the implications of the composition of liveweight gain on feed conversion ratios

3.2 Producer survey

The participant information sheet and the survey questions were approved by the Charles Sturt University Human Ethics Committee (protocol number H19236). Participation in the survey was voluntary and anonymous, and consent was implied by completion of the survey.

3.2.1 Design and inclusion criteria

A cross-sectional survey was published online via SurveyMonkey™ (http://www.surveymonkey. com) and made publicly available for 11 weeks from 14 February until 1 May 2020. The target population was Australian lamb producers who finish lambs in intensive feeding systems (feedlots). We aimed for as many responses as possible from a diverse geographical distribution within the country. Inclusion criteria were that the lamb producer resides in Australia and must own or manage a lamb feedlot that was considered ‘currently active’ by the participant.

The questionnaire consisted of five sections: ‘demographics and farm characteristics’, ‘lamb description and management’, ‘nutrition’, ‘health’ and ‘resources and knowledge’. The demographic and farm characteristics questions included questions relating to the location and size of the property, feedlotting experience of the operator, typical months of use, enterprise type, number of lambs finished annually, capacity of feedlot, density of lambs, yard structure and shade type. The lamb description and management section included questions regarding lamb breed and source, entry age and weight, induction protocols, target finishing weights, mob sizes, weighing and drafting frequency, and average daily liveweight gain. The nutrition questions included those relating to feed conversion ratio (FCR), feed testing, ration design, feed delivery method, vitamin and mineral supply, and water supply. The health section included questions on shy feeder occurrence, shy feeder management, mortality percentage, mortality causes and conducting post-mortem examinations. Finally, questions in the resources and knowledge section asked what resources were accessed to assist in design of the feedlot and management of the lambs, along with an open response question regarding the perceived knowledge gaps in the lamb feedlotting industry.

3.2.2 Distribution

The survey was advertised through the researchers' existing networks and the link to the survey was distributed on Facebook (Facebook, 2020) and Twitter (Twitter, 2020). Industry professionals and feed manufacturers, which Charles Sturt University has previously collaborated with, were contacted and requested to distribute the survey on behalf of the research team. The method of distribution of the link to the survey (for example newsletters, email or through social media) was at the discretion of these organisations.

3.2.3 Statistical analysis and calculations

Descriptive analyses, including frequencies, percentages, medians, means and standard deviations, were conducted in R (R Core Team 2018). Percentages were calculated among those who responded to each specific question.

For the purpose of this analysis, multiple response categories were collapsed into fewer categories or combined to create new variables. For example, the median value for average annual lambs finished was used to designate lamb feedlots as either small feedlots (≤1500 lambs) or large feedlots (>1500 lambs). Additionally, rainfall zone was reported via a closed-ended question with multiple options, and subsequently these categories collapsed into high rainfall (≥500 mm/year) and low rainfall (<500 mm/year) regions.

The 'area provided per lamb' was calculated by first dividing the 'total lamb capacity' of the feedlot by the 'number of pens', which equated to 'mean pen capacity'. The 'mean pen capacity' was then divided by the response to 'area per pen'. Similarly, the 'shade provided per lamb' estimate used the 'area provided per lamb' value and multiplied the respondent's answer for the 'proportion of the pen shaded'. The feedlot utilisation rate was calculated by dividing the 'average annual lambs finished' by the 'total lamb capacity' of the feedlot.

3.3 Monitoring lamb growth rates on commercial farms (2017-2019)

A survey of pre- and post-weaning lamb growth rates on commercial farms was conducted which tracked liveweight change in individual lambs that had been fitted with electronic ear tags. It was hypothesised that lamb growth rates pre-weaning are approximately what might be expected in non-limiting conditions and it is post-weaning that lamb growth rates are much lower than expected genetic potential.

Lamb growth rates both pre- and post-weaning were measured on 11 farms in south-eastern Australia. On some farms a portion of the flock (500 lambs; between 5 and 20% of lambs finished) was measured and on other farms the whole flock was measured (lamb numbers ranged from 90 to 2499). Pre-weaning growth rates were calculated by liveweight measurements at either birth or lamb marking and again at weaning. Post-weaning growth rates were calculated from liveweight at weaning and again at approximately six to eight weeks post-weaning.

All livestock management was approved by the Charles Sturt University (CSU) Animal Care and Ethics Committee (protocol number A19252).

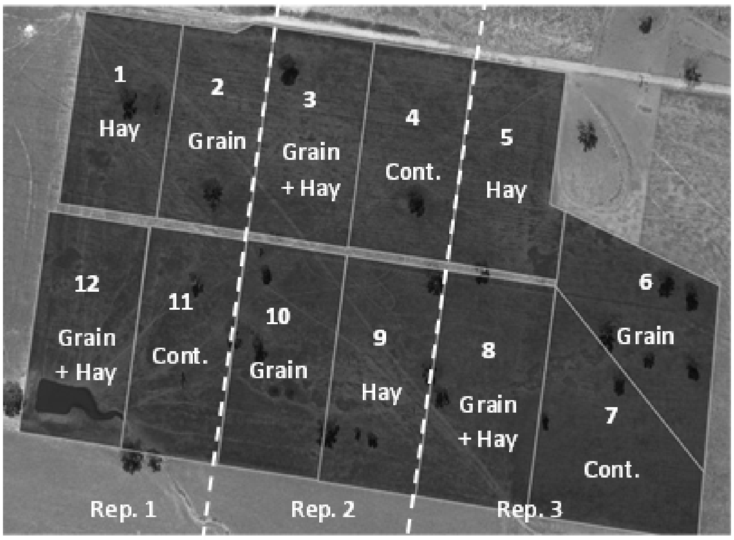
3.4 Experiment 1: Optimising preparation and adaptation of lambs to increase feed intake and subsequently growth rate

Border Leicester x Merino maiden ewes (*n*=244) identified as bearing single fetuses from the five-week joining to Poll Dorset and White Suffolk rams were sourced from a commercial farm. The ewes commenced lambing on 30 August 2019. Mixed sex lambs (female and desexed male) were exposed to different nutritional management on pasture both pre- and post-weaning before entering a feedlot for a finishing period. CT scans were used on a portion of lambs to measure changes in body composition.

3.4.1 Site management

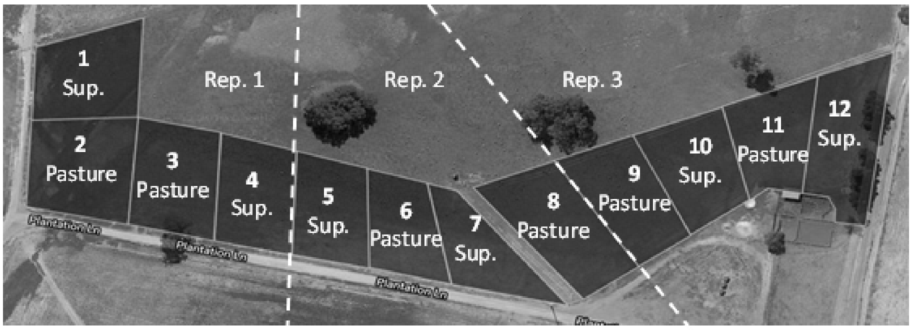
The experiment was conducted from October 2019 to February 2020 across three sites. The pre-weaning paddock was a 30-hectare (ha) paddock sub-divided into 12 plots approximately 2.5 ha each (Figure 1). Pastures consisted mainly of annual grasses (*Lolium multiflorum, Hordeum leporinum, Vulpia myuros*) and subterranean clover (*Trifolium subterraneum*) and were considered to be typical of high-quality spring pastures in southern NSW and of sufficient quantity (>2 t DM/ha) to not restrict animal intake.

Figure 1. Plot layout of the paddock used for creep-feeding lambs at the commercial farm in southern NSW (pre-weaning paddock).



The weaning paddock was a 3-ha portion of a paddock sub-divided into 12 plots approximately 0.25-ha each (Figure 2). The paddock was sown to lucerne (*Medicago sativa*) in 2017; species present were predominantly lucerne and subterannean clover (*Trifolium subterraneum*) and some annual grasses (*Lolium multiflorum, Hordeum leporinum*).

Figure 2. Plot layout of paddock used to graze lambs on pasture post-weaning at the commercial farm in southern NSW (weaning paddock).



The CSU Lamb Feeding Facility contains 36 bare-earth pens, with each pen approximately 24 m^2 including a 7 m^2 shaded area located in Wagga Wagga, southern NSW (Figure 3).

Figure 3. Layout of 36 bare-earth pens used for feeding lambs in experiments at Charles Sturt University in southern NSW (CSU Lamb Feeding Facility).

3.4.2 Experimental design

The experiment was a replicated factorial design with four pre-weaning treatments (pre-weaning paddock), three post-weaning treatments (post-weaning paddock and CSU Lamb Feeding Facility) and a feedlot evaluation phase at the CSU Lamb Feeding Facility (Figure 4).

In the pre-weaning phase, lambs were provided one of four treatments (Table 1) by excluding ewes from a supplementary feeding area by a panel with 250 mm gaps between vertical bars. Each plot was provided with creep access to either lucerne hay (fed on ground), a loose grain ration in a self-feeder or both the grain ration and lucerne hay. The loose grain ration was comprised of 70% whole barley, 25% whole lupins and 5% a commercial vitamin, mineral and rumen buffer pre-mixed pellet (VitaMinBufTM; CopRice, Australia). A control plot in each replicate had no access to supplementary feed.

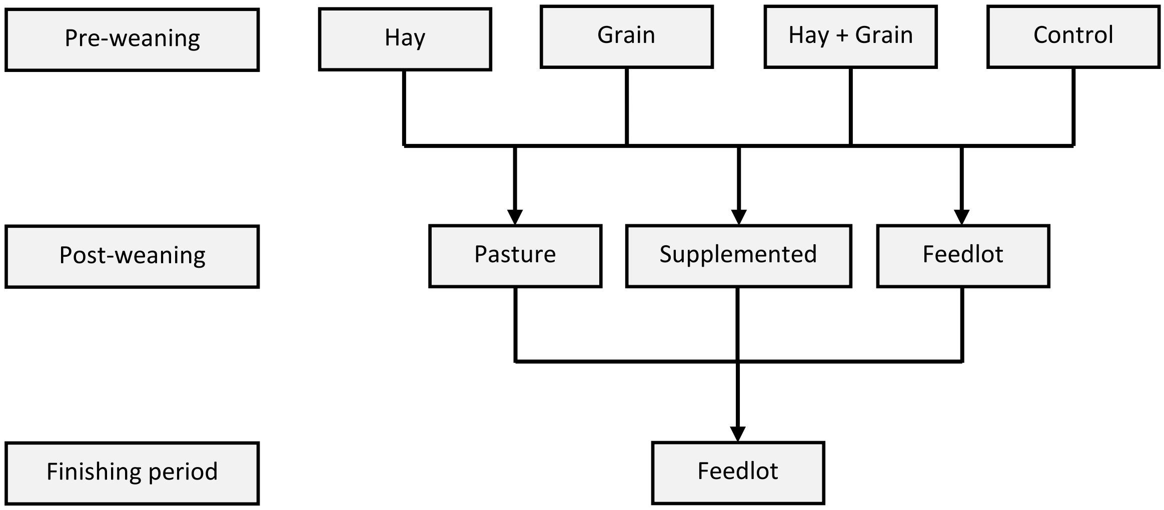


Figure 4. During the pre-weaning phase (16 October to 30 November) lambs were with ewes with access to hay, grain, hay + grain or no supplement (control); during the post-weaning phase (30 November to 29 December) lambs were allocated to pasture, pasture with access to grain supplement or into a feedlot; during the finishing phase (29 December to 7 February) all lambs were fed in the feedlot.

In the 30 day post-weaning phase, four-month-old lambs were provided one of three treatments including grazing irrigated lucerne pasture with or without access to the loose grain ration in self feeders and entering the feedlot to be fed the loose grain ration with the separate provision of ad libitum lucerne hay for the induction period and straw thereafter fed in hay racks (Table 1).

Table 1. Combined nutritional management treatments before entering the CSU Lamb Feeding Facility for the finishing period. Hay; lucerne hay creep-fed pre-weaning, grain; mixed grain ration creep-fed pre-weaning, supplemented; mixed grain ration provided in self-feeders supplementary to pasture.

Treatment group	Pre-weaning	Post-weaning
1	Hay	Pasture
2	Hay	Supplemented
3	Hay	Feedlot
4	Grain	Pasture
5	Grain	Supplemented
6	Grain	Feedlot
7	Grain + Hay	Pasture
8	Grain + Hay	Supplemented
9	Grain + Hay	Feedlot
10	Control	Pasture
11	Control	Supplemented
12	Control	Feedlot

The 39-day finishing period commenced at the conclusion of the 30-day post-weaning period when lambs grazing lucerne pasture entered the feedlot. Lambs were giving ad libitum access to the loose grain ration and straw following an 18-day induction period.

A sample of lambs (*n*=112) from all treatments were balanced for sex and CT scanned at both entry to the feedlot (irrespective of feedlot entry during the post-weaning phase or finishing phase) and the conclusion of the experiment using the CT scanner located at the Veterinary Clinical Centre (VCC) at CSU Wagga Wagga. CT scanning methodology is described in section 3.7.

3.4.3 Animal management

All livestock management was approved by the CSU Animal Care and Ethics Committee (protocol number A19301).

The experiment began at lamb marking on 16 October. All ewes and lambs were brought into nearby sheepyards and lambs (*n*=228) were drafted off their mothers. Lambs were weighed using a lambing box as they exited the lamb marking cradle before being reunited with their dam and randomly allocated to one of 12 plots in the pre-weaning paddock (Figure 1).

On 30 November, all ewes and lambs were brought into nearby sheepyards for weaning and all lambs were weighed. Lambs from each of the 12 plots in the pre-weaning paddock were split into three groups so that there were six to seven lambs from each pre-weaning plot in each of the pasture, pasture with grain supplement or directly to feedlot post-weaning treatments (Table 1).

The third group of lambs were transported to the CSU Lamb Feeding Facility and were allocated to one of 12 pens at the feeding facility and immediately commenced an 18-day induction period to adapt the lambs to the feedlot ration. During induction, the grain ration was fed in plastic troughs, starting at 100 g/head/day, and increasing the daily allocation every third day by 150 g/head/day until 700 g/head/day on day 15. Lambs were given ad libitum access to small bales of lucerne hay fed in racks. On days 16-18, lambs were given ad libitum access to the loose grain ration in self-feeders and over the three days, small bales of barley straw were substituted for the lucerne hay to encourage consumption of the mixed grain ration. Nutritional values of feedstuffs are included in the results. On 2 December, three randomly selected lambs from pens 1 to 12 at the CSU Lamb Feeding Facility were CT scanned.

On 29 December, the finishing phase commenced and all lambs were weighed and lambs in the post-weaning paddock were transported to the CSU Lamb Feeding Facility to commence the 18-day induction period described above before ad libitum feeding. On 3 January, two lambs from pens 21 to 36 and one lamb from pens 13 to 20 at the CSU Lamb Feeding Facility were CT scanned. On 5 and 6 February all lambs previously CT scanned were re-scanned and on 7 February all lambs were weighed to conclude the experiment.

3.4.4 Sample analysis

Two samples of the loose grain mix, two lucerne hay samples and a single barley straw sample were collected and analysed. All samples were dried at 60°C for 48 hours before delivery to a commercial analytical laboratory (NSW Department of Primary Industries, Wagga Wagga NSW, 2650) for determination of nutritive value via near-infrared spectroscopy as described by Packer et al. (2011).

3.4.5 Statistical analysis

Estimated empty body, fat and lean rate of gain calculations were derived from CSIRO (2007) using grain intake data only (due to likely errors in measurement of hay and straw intake) and predicted means reported for all lambs irrespective of treatment.

Data was analysed by generalised linear models using ASRemL (Gilmour et al. 2009). Lamb weights, growth rates, reticulorumen volume, feed intake and empty body composition were modelled using a linear univariate model with fixed effects of treatment, sex, weaning weight, appropriate two-way interactions, and replicate and pen/plot within replicate as random effect.

3.5 Experiment 2: Level of feeding and stage of maturity affects diet digestibility and protein and fat deposition in cross-bred lambs

Twin born lambs from the single-sire joining of 18-month-old Merino x Border Leicester ewes to either Poll Dorset or White Suffolk rams were sourced from a commercial farm in southern NSW. Birth date, birth weight, sires and siblings were known from lambing data. Lambs were mixed sex (female and desexed male) and balanced for sex and sire across treatment groups. A feeding trial used CT scans to measure changes in body composition over time with a sequentially run animal house-based study for the determination of nutrient digestibility.

3.5.1 Site management

The experiment was conducted at the CSU Lamb Feeding Facility and NSW Department of Primary Industries (NSW DPI) Animal Nutrition Unit, both located in Wagga Wagga in southern NSW. The CSU Lamb Feeding Facility contains 36 bare-earth pens, with each pen approximately 24 m^2 including a 7 m^2 shaded area (Figure 3). The NSW DPI Animal Nutrition Unit contains indoor individual animal pens, each approximately 2 m^2, and metabolism crates for the collection of faeces and urine.

Paddocks used on the commercial farm prior to feeding periods were a weaning paddock which was sown to lucerne (*Medicago sativa*) in 2017 and also contained subterranean clover (*Trifolium subterraneum*) and some annual grasses (*Lolium multiflorum, Hordeum leporinum*), and a pasture paddock with naturalised pasture which consisted mainly of annual grasses (*Lolium multiflorum, Hordeum leporinum, Vulpia myuros*) and subterranean clover (*Trifolium subterraneum*).The weaning paddock was considered to be typical of high-quality spring pastures in southern NSW and both paddocks contained sufficient quantity (>2 t DM/ha) to not restrict animal intake.

3.5.2 Experimental design

The replicated experiment had high (H) and low (L) feeding level treatments in two feeding periods (P1 and P2). Treatments are referred to as H1 and L1 for P1 and H2 and L2 for P2. One hundred and eight lambs were blocked by sire and sex and then stratified by age before being randomly assigned to pens containing three lambs each. Each day a weighed amount of a pelletised ration (Tables 2 and 3) was provided to each pen in a self-feeder and any refusals from the previous day were collected and weighed. The ration was designed to contain the nutrients necessary for a growing lamb (CSIRO 2007). A separate batch was manufactured for each feeding period with wet chemistry analysis of each batch conducted prior to each feeding period (Table 3).

Table 2. Ingredients of experimental ration provided to lambs.

Ration component	%
Barley	46.9
Cereal hay	20.0
Lucerne hay	20.0
Canola meal	5.0
Millmix	4.9
Limestone	1.5
Canola Oil	1.0
Salt	0.6
Mineral mix	0.1

Lambs on H feeding levels were fed the pelleted diet at a rate equivalent to 3.5% of the most recent mean liveweight (LW) of combined H treatment lambs as dry matter (DM). Similarly, each lamb in the L treatment was allocated 2.5% of the mean LW of the L treatment lambs as DM. The lambs entered the feeding facility for an eight-week feeding period at a mean age of 100 (± 3.7 SD) days and then again for P2 at a mean age of 230 (± 3.7 SD) days. Half of the lambs that were previously allocated to H1 were switched to L2 and vice versa. The remaining lambs stayed in their allocated feeding levels for P1 and P2, thus creating four feeding treatment groups: HH, HL, LH, and LL. Lamb LW was recorded prior to CT scanning at the start and conclusion of the feeding periods and was recorded fortnightly whilst at the feeding facility to adjust daily ration allocation. All lambs were CT scanned at the Veterinary Clinical Centre (VCC) at CSU. CT scanning methodology is described in section 3.7.

Table 3. Wet chemistry analysis and digestibility of pelleted diet provided to lambs during each feeding period on a dry matter basis with calculated metabolisable energy density (M/D; MJ ME/kg DM) (± SE) by direct measurement.

	Feeding period 1		**Feeding period 2**		
	Composition (%)	Digestibility[A] (%)	Composition (%)	Digestibility (%)	
				Low	**High**
Dry matter	93	71.5 ± 0.9	93	71.1 ± 0.4[a]	67.3 ± 0.4[b]
Organic matter	92	68.3 ± 0.8	92	67.9 ± 0.4[a]	64.5 ± 0.4[b]
NDF	32	47.3 ± 1.5	26	44.8 ± 1.3	
ADF	14	36.5 ± 1.4	13	41.9 ± 1.8	
Crude protein	17	72.7 ± 1.1	17	74.7 ± 0.5[a]	68.8 ± 0.5[b]
Gross energy	17.8	71.7 ± 1.1	18.4	69.9 ± 0.5[a]	65.7 ± 0.5[b]
M/D[B]	-	11.3 ± 0.2	-	11.0 ± 0.1[a]	10.4 ± 0.1[b]

[A] No significant difference in diet digestibility between low and high feeding level in period one.

[B] Calculated by predicting methane (CH_4) production as 20.8 g CH_4 per kg dry matter intake (Charmley et al. 2015).

Prior to each feeding period, a 16-day induction period, starting at 100 g/head/day and increasing the daily allocation by 50 g/head/day, allowed the lambs to adapt to the ration. The first nine days of both induction periods occurred in the paddock on the commercial farm where the lambs were located which enabled continued access to pasture. After nine days, the lambs were transported to the feeding facility to continue the induction period with access to barley straw for seven days before commencing the feeding period.

The metabolisable energy and digestibility of the diet was determined by two six-day faeces and urine collection periods with H and L intake treatments. Ten twin-born and reared lambs of mixed sexes were assigned to treatments so that they were balanced for sire, sex, LW and age with each sibling allocated to different treatments for both feeding periods. Lambs were a median age of 117 (± 2.5 SD) and 247 (± 2.5 SD) days at the commencement of the first and second collection periods respectively. Lambs were individually housed in metabolism crates and each day a weighed amount of a pelletised ration (Tables 2 and 3) was provided to each lamb in a feeder and any refusals from the previous day were collected and weighed. Each lamb in the H and L treatments were inducted to the ration and fed at the rates as outlined above.

3.5.3 Animal management

All livestock management was approved by the CSU Animal Care and Ethics Committee (protocol number A20203 and A20305).

Prior to weaning, the lambs were exposed to grain by trail feeding whole barley to ewes and lambs on five separate occasions. The induction period for P1 commenced on 6 October 2020, with lambs (*n*=136) being fed in plastic troughs in the paddock. On 15 October 2020, all lambs were brought into nearby sheep-yards and 108 were allocated to pens before being transported to the feeding facility. The remaining 28 lambs were either allocated to the digestibility experiment (*n*=10) or returned to the weaning paddock to be kept as spares. Thirty-four of the 36 pens at the feeding facility contained three lambs of the same gender and sire with a birth date within six days of each other. Two pens contained three lambs of the same gender but different sires.

The first feeding period commenced on 22-23 October 2020. Weighing and CT scanning of lambs was conducted before the daily ration was fed and lambs were not removed from their pens for longer than two hours. On 17-18 December 2020, all lambs were weighed and CT scanned to conclude P1. The lambs were returned to the commercial farm to graze pasture until the commencement of P2. On 20 December 2020, all lambs were shorn. The induction period for P2 commenced on 13 February 2021. On 22 February 2021, all lambs were brought into nearby sheep-yards and 107 lambs that completed P1 and one replacement (H2 treatment), were allocated to pens and transported to the feeding facility. The remaining spare lambs took no further part in the experiment.

On 1-2 March 2021, all lambs were weighed and CT scanned as described for P1. On 5 March 2021, approximately 50% of lambs from both treatments exhibited signs of subclinical acidosis and all lambs were returned from 1000 g/head/day to a feeding level of 500 g/head/day for two days before increasing by 50 g/head/day. The occurrence of subclinical acidosis was attributed to a batch change in the pelleted diet being fed. During this period the lambs were additionally provided daily with a weighed amount of lucerne hay which was included in intake calculations. Once lambs had achieved intake of 900 g/head/day, hay was withdrawn, the feeding period recommenced and was extended by 10 days. The experiment concluded on 6-7 May 2021, when all lambs were weighed and CT scanned before being returned to the commercial owner.

The ten lambs used for the determination of metabolisable energy and digestibility of the diet were managed prior to each feeding period as outlined above. Lambs were held in one of two pens consisting of the five lambs for each treatment for seven days at the CSU Lamb Feeding Facility before being weighed and transported to the NSW DPI Animal Nutrition Unit to be housed and fed in individual pens for a further seven days. Lambs were transferred to individual metabolism crates for two days before the six-day collection periods commenced.

After the first collection period, lambs were returned to the commercial farm to graze pasture until the conclusion of P1 when all lambs were reunited. Three of the lambs that were allocated to the H treatment for the first collection period were switched to the L treatment for the second collection period and vice versa. At the conclusion of the second collection period, all lambs were returned to the commercial farm and took no further part in the experiment.

3.5.4 Sample analysis

All analytical procedures, with the exception of the determination of gross energy (GE) of samples from the second collection period, were undertaken at the Feed Laboratory of NSW DPI at Wagga Wagga, NSW. Analysis of GE of samples from the second collection period was undertaken at ALS Laboratory Group, Lithgow NSW.

The frozen faecal and feed samples were dried in an air-forced oven to a constant weight at 70°C to determine their DM content (AFIA 2014). The ash content was determined by the combustion of a 2 g sample at 600°C for six hours, from which the organic dry matter (OMD) content was calculated. The N content of feed and faeces (0.2 g ground samples) were determined using a Leco CNS 2000® analyser (Leco, St Joseph, MI, USA), from which the crude protein (CP) content was calculated by multiplying the N content by a factor of 6.25. The GE of feed and faeces was determined by measuring the heat of combustion of a pelleted sample in a bomb calorimeter (Basolo et al. 2020).

The neutral detergent fibre (NDF) content of the feed and faeces was determined by weighing approximately 0.5 g (known weight) of each sample into an ANKOM filter bag and placed in the ANKOM Fibre Analyser (Ankom® 200/220 fibre analyser, ANKOM technology, Macedon NY, USA) vessel along with neutral detergent solution, sodium sulphite and heat stable alpha-amylase. The bags were heated and agitated for 75 min and then rinsed three times with hot water and alpha-amylase. The bags were then soaked in acetone for 3-5 min and then dried in an oven at 105°C for 2 h (AFIA 2014).

The acid detergent fibre (ADF) content of the feed and faeces was determined by weighing approximately 0.5 g (known weight) of each sample into an ANKOM filter bag and placed in the ANKOM Fibre Analyser (Ankom® 200/220 fibre analyser, ANKOM technology, Macedon NY, USA) vessel along with acid detergent solution. The bags were heated and agitated for 60 min and then rinsed three times with hot water. The bags were then soaked in acetone for 3-5 min and dried in an oven at 105°C for 2 h (AFIA 2014).

The frozen urine samples were thawed overnight at room temperature. The carbon (C) content of urine samples (0.2 g samples) were determined using a Leco CNS 2000® analyser (Leco, St Joseph, MI, USA).

3.5.5 Statistical analysis

Individual apparent digestibility (%) of feed was calculated on a DM basis from the difference between total faecal output and total intake less any refusals during the six-day period. Energy balances were produced from the difference between total intake and total faecal and urinary output during the six-day period. For direct measurement of metabolisable energy (ME) density of the diet, methane (CH_4) production was predicted as 20.8 g CH_4 per kg DM intake (Charmley et al. 2015) and gross energy (GE) of urine predicted using the equation of Blaxter et al. (1966): 9.66 kcal/g

C – 3.0. Energy balance calculations to determine maintenance energy requirements and the efficiency of growth were derived from CSIRO (2007) and mean values reported for each feeding period.

Body composition and digestibility experiment data were analysed by generalised linear models using ASRemL (Gilmour et al. 2009). Lamb weights, growth rates, stomach volume, stomach contents, feed intake and empty body composition were modelled using a linear univariate model with fixed effects of treatment, sire, sex, birthweight, age, feeding period one start weight, appropriate two-way interactions and pen as random effect. Diet digestibility, energy balances and feed intake from the digestibility experiment were modelled using a linear univariate model with fixed effects of treatment, sire, sex, appropriate two-way interactions and sibling as random effect.

3.6 Experiment 3: The effects of diet composition and grazing on the rate of lean and fat deposition in composite lambs

A feeding trial used CT scans to measure changes in body composition over time in composite breed wether lambs (*n*=48) sourced from the CSU Farm.

3.6.1 Site management

The experiment was conducted at the CSU Lamb Feeding Facility located in Wagga Wagga in southern NSW. The CSU Lamb Feeding Facility contains 36 bare-earth pens, with each pen approximately 24 m^2 including a 7 m^2 shaded area (Figure 3).

Paddocks used on CSU Farm included a small and large lucerne paddock. Both paddocks were sown to lucerne (*Medicago sativa*) in 2017 and also contained subterranean clover (Trifolium subterraneum) and some annual grasses (Lolium multiflorum, Hordeum leporinum).

3.6.2 Experimental design

Lambs were allocated ad hoc to one of three treatments for a 41-day experimental period. Treatments included:

1. Fed a barley grain-based pellet comprising 30% lucerne chaff in confinement (Pellet 1; Table 4)
2. Fed a barley grain-based pellet without lucerne chaff (Pellet 2; Table 4), but with lucerne hay offered to lambs separately in confinement
3. Lambs grazing lucerne pasture in a paddock

Nutritive values of the feed sources are reported in Table 4. The pelleted rations were designed so that one pellet had lucerne chaff incorporated into the pellet while the other did not and would have lucerne hay offered separately in a trough.

Table 4. Nutritive values of lucerne pasture, lucerne hay and pelleted concentrates on a dry matter (DM) basis provided to lambs during the experiment.

	Lucerne pasture	Lucerne hay	Pellet 1	Pellet 2
Dry matter (%)	25.7	90.9	91.0	91.5
Neutral Detergent Fibre (% DM)	30.7	51.5	27.5	23.7
Acid Detergent Fibre (% DM)	15.3	38.1	11.0	7.8
Crude Protein (% DM)	29.1	14.6	17.7	15.1
DMD (% DM)	79.0	57.0	75.0	81.0
DOMD (% DM)	74.0	55.0	74.0	79.0
Organic Matter (% DM)	89.0	90.0	90.0	91.0
M/D (MJ ME/kg DM)	12.0	8.2	12.1	12.5

All lambs from all treatments were CT scanned at the start and finish of the experimental period using the CT scanner located at the Veterinary Clinical Centre (VCC) at CSU Wagga Wagga. CT scanning methodology is described in section 3.7.

3.6.3 Animal management

Lambs were drafted from a larger mob on 11 April 2022 and transported to the feeding facility (Treatments 1 and 2) or a paddock containing lucerne pasture. Lambs in Treatment 1 and Treatment 2 were allocated to pens at the CSU Lamb Feeding Facility with 2 lambs allocated to each pen. For the first 2 weeks lambs were slowly introduced to their diet following the NSW DPI protocol (Duddy et al. 2016) and with ad libitum access to lucerne hay. Lambs in all treatments were yarded undercover at 4pm on Thursday 28 April to avoid impending rainfall impacting weight. At 8am on 29 April, lambs were weighed and transported in groups for CT scanning at the Veterinary Clinical Centre (VCC) at CSU Wagga Wagga before returning to their pens or paddock. Four spare lambs had been fed in the feeding facility to this point. One of the spare lambs that had been inducted on the same diet was used as a replacement for a lamb in the feeding facility that was removed during the induction period following a veterinary inspection.

The lambs in the lucerne treatment were initially put in a small paddock containing mainly lucerne pasture. During the first 2 weeks lambs had access to straw, but from the start of the main feeding trial the straw was removed and lambs only had access to pasture. It was identified at the end of the feedlot induction period that one of the lambs had not been castrated, and this lamb was replaced by one of the spare lambs that had been removed from the CSU Lamb Feeding Facility. On 19 May the lambs were moved to a larger paddock with fresh lucerne as their previous paddock was required for cattle.

From 29 April the amount of pellets were gradually increased to a maximum of 4.5 kg offered (on an as fed basis) per pen per day for Treatment 1 and 3.65 kg pellets per pen per day plus ad libitum access to lucerne hay for Treatment 2. If lambs in a pen did not eat all of their pellets or hay from the preceding day, the amount fed was reduced to encourage consumption. Poor weather and mud in the pens resulted in frequent spoilage of hay, and refusals were removed on 6th, 16th, 20th, 30th May and 2nd June. These refusals were weighed and a sub-sample dried at 70°C for 48 h to calculate dry matter content of the refusals. Consumption was calculated from the equation:

Amount pellets fed x DM % + amount hay fed x DM % - amount refusals x DM %

Lambs in all treatments were yarded undercover on Wednesday 8 June. Lambs in Treatment 3 were removed from the lucerne paddock at 1pm due to the time required yard and transport them from the paddock, whereas lambs in Treatments 1 and 2 were yarded at 4pm. At 8am on 9 June, lambs were weighed and transported for CT scanning.

Following scanning, lambs were put in a paddock as a single group with volunteer grasses and access to straw and water. At 11am, on Monday 13 June lambs were yarded and trucked at 2pm to Gundagai Meat processors for slaughter. Measurements at abattoir included IMF, percentage bone, muscle and fat (via DEXA scans) carcase weight and pH decline.

3.6.4 Sample analysis

Samples of both pelleted rations, lucerne pasture from both paddocks and a lucerne hay sample were collected and analysed. All samples were dried at 60°C for 48 h before delivery to a commercial analytical laboratory (NSW Department of Primary Industries, Wagga Wagga NSW, 2650) for determination of nutritive value via near-infrared spectroscopy as described by Packer et al. (2011).

3.6.5 Statistical analysis

Data was analysed by generalised linear models using ASRemL (Gilmour et al. 2009). Lamb weights, growth rates, reticulorumen volume, feed intake and empty body composition were modelled using a linear univariate model with fixed effect treatment.

3.7 CT scanning

3.7.1 CT scanning method

Lambs that were CT scanned in Experiments 1-3 were individually moved through the CT scanner (16 Slice Toshiba Alexion Advance) in a cradle in an upright position with their legs underneath their body (Appendix 9.3). The X-ray tube energy setting was 120 kV. Cross-sectional slices (5 mm width) were taken between the 4th cervical vertebrae and the 1st sacral vertebrae, yielding an average of 120 images per animal. CT images at 30 mm intervals were manually edited (OsiriX https://www.osirix-viewer.com/, accessed 2021; Rosset et al. 2004) to separate the reticulo-rumen, omasum and abomasum (stomach contents), carcass components and visceral organs.

Figure 5: Lamb moving through the CT scanner at the Veterinary Clinical Centre at Charles Sturt University.

The proportion of stomach-fill components (gas, particulate and liquid) and the composition of the empty body (stomach contents removed), carcass and viscera (fat, lean and bone) were then determined using Image J (v1.53, https://imagej.nih.gov/ij/, accessed 13 January 2021) to create a distribution of pixels in grayscale units from 0 to 256. Boundaries for gas, particulate and liquid were set to 0-1, 2-65, and 65-256 respectively. Boundaries for fat, lean and bone were set to 10-90, 91-200, and 201-256 respectively. The proportion of each component was found from the sum of all slices which were then corrected for density (Fullerton 1980). The stomach volume was calculated within the computer program OsiriX with CT images at 15 mm intervals.

3.7.2 Body composition calculations

Calculations of empty body tissue masses and rates of gain required a combination of liveweight, CT scan data, an estimation of the weight of contents of the reticulo-rumen, omasum and abomasum (stomach) to correct for gut fill and an estimation of fleece weight. Fleece-free empty body weight (FFEBW) was estimated using liveweight less the estimated weight of stomach contents and estimated weight of the greasy fleece. The proportion of tissues in the empty body were calculated using CT images at 30 mm intervals with the sum of all slices corrected for density (Fullerton 1980) and multiplied by estimated FFEBW to determine tissue weights.

The volume of the stomach and viscera were calculated using OsiriX. Stomach contents and viscera tissue mass were estimated using the approximate volume and proportions of tissue components. The weight of stomach contents was estimated on the basis that the density of the contents was one for experiments 1 and 3 (Goopy et al. 2014). For experiment 2, stomach contents weight was estimated from 48 lambs using calculations of stomach volume and the proportions of stomach contents (gas, particulate and liquid) from CT images at 30 mm intervals. The proportion of each component was found from the sum of all slices which were then corrected for density (Fullerton 1980). The data from all four CT scans of 48 lambs were then combined to develop a linear equation using stomach volume to estimate stomach contents weight to correct for gut fill and calculate FFEBW for all 108 lambs involved in the experiment (Figure 6). For experiment 3, FFEBW was multiplied by 0.86 to allow for the approximate weight of the head, feet and skin using the data from Hegarty et al. (1999) and Dougherty et al. (2022). This value was then used to calculate carcass weights by subtracting the calculated weights of viscera tissues.

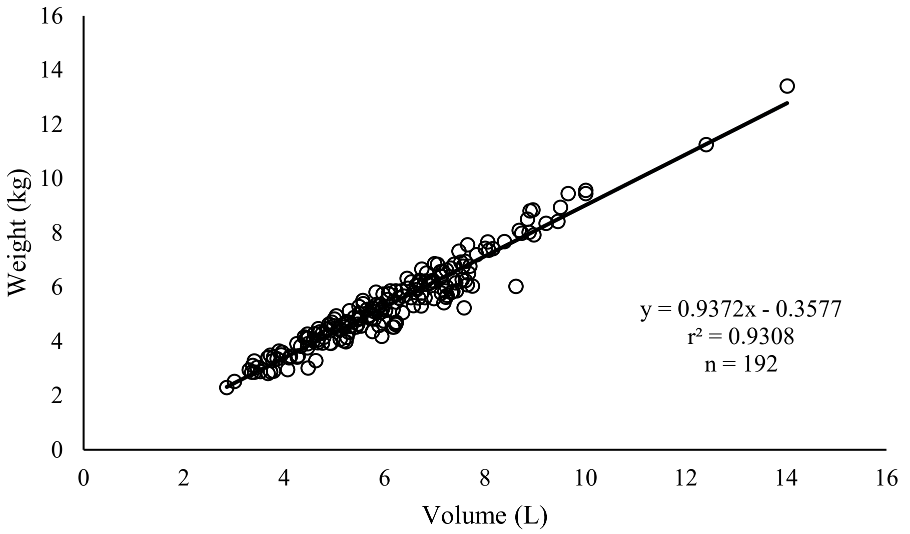


Figure 6. Relationship between volume and weight of reticulo-rumen, omasum and abomasum estimated by CT scanning.

3.8 Modelling lamb growth

3.8.1 Description

The accuracy of two lamb growth models (CSIRO 2007; Oddy et al. 2022) was assessed using live animal CT scan data from a feeding trial in which lambs were fed two feeding levels at two stages of maturity. The data used was a subset of a lambs involved in Experiment 2. Sixteen pens (*n*=48 lambs) from were randomly selected for this investigation and were balanced for sex and treatment. Equations for the models (CSIRO 2007; Oddy et al. 2022) were computed using Excel (Microsoft 2019) to predict FFEBW, liveweight, lean and fat tissue gain during both feeding periods and body composition at the conclusion of each period for H and L feeding level treatments.

The model described by Oddy et al. (2022) additionally separates lean tissue into both NVEB and viscera components which are presented here both separately and combined as lean tissue for comparisons with CSIRO (2007). A standard reference weight of 70 kg was used for both models with the proportion of initial fleece free liveweight to standard reference weight used to determine stage of maturity. In the CSIRO (2007) model, the energy value of protein including wool (23.6 kJ/g) and fat (39.3 kJ/g) were as described by CSIRO (2007) and protein was determined to be 22% of fat-free mass (Oltjen et al. 2006). The Oddy et al. (2022) model used similar values for protein (23.8 kJ/g) and fat (39.6 kJ/g) and protein was determined to be 21% of fat-free mass in the NVEB and 15.7% of fat-free mass in the viscera (Dougherty et al. 2020).

Gut fill is estimated in the model by Oddy et al. (2022) by utilising data from Butterfield (1988) on changes in gut contents due to stage of maturity with an adjustment for the energy density of the diet consumed. The CSIRO (2007) model estimates rate of gain of empty body tissues and liveweight gain; therefore, gut fill is determined by the initial value for gut fill calculated from CT scans and the difference between empty body tissue and liveweight gain minus fleece. It was required that the same fleece growth model be utilised by both models for the observed values as any discrepancy would have affected predicted gut fill.

Clean fleece rate of gain was determined by an animal age and breed factor multiplied by metabolisable energy intake which was divided by 0.7 to allow for the approximate ratio of greasy fleece weight to clean fleece weight (Oddy et al. 2022). The fleece was estimated to weigh 1.5 kg at the commencement of both feeding periods due to the lambs being shorn shortly after the conclusion of the first feeding period.

3.8.2 Statistical analysis

The observed mean rates of tissue, empty body weight and LW gain were calculated on a pen basis (three lambs per pen) as individual animal energy intake was unknown. The models were then run separately for each pen using the initial values for body composition as determined by CT scans and ME intake averaged over the feeding periods. The initial values (Table 1) were subtracted from the model predicted body composition at the end of the feeding period and divided by the number of days in the feeding period to calculate model predicted rate of gain.

A comparison of model predicted rate of gain and observed values were evaluated using RStudio (RStudio Team 2020). The coefficient of variation of observed values and mean bias as a percentage of the observed means are reported (Table 2). Rate of gain mean bias was calculated as the sum the observed value minus the predicted value for all pens by treatment within feeding period, divided by the number of involved pens. Mean square prediction error (MSPE) for rate of gain was calculated as the sum of the squared observed value minus the predicted value for all pens by treatment within feeding period, divided by the number of involved pens. The root mean square prediction error (RMSPE) was the square root of the MSPE. Mean bias and RMSPE were used as a measure of the accuracy of the predicted values as they are in the same unit as the observed value.

The MSPE was decomposed into overall bias, slope bias and random error as provided by Ellis et al. (2009). The overall bias calculated the bias of the prediction and is zero when the mean predicted value coincides with the mean observed value. The slope bias calculated the error due to deviation of the regression slope from unity and the random error calculated the error due to disturbance, or the portion of the MSPE that cannot be eliminated by linear corrections of the predictions. Random error largely reflects random variation affected by the method of data collection and inevitable measurement errors.

4. Results

4.1 Literature Review

The researchable questions identified from the literature review include:

a) What are the effects of supplementing pasture with ad libitum access to grain on feed intake, diet digestibility and liveweight gain with varying pasture supply?
b) How much of the change in liveweight following weaning is attributed to changes in gut fill and organ size and how does this alter with weaning age?
c) Does familiarising lambs with a diet increase nutrient intake post-weaning both whilst grazing pasture and in a feedlot environment?
d) Is nutrient intake the major constraint on lamb growth in intensively fed lambs? What other constraints exist?
e) Why are pasture fed ruminants typically leaner than those fed a high-concentrate diet in confinement and what are the activity energy costs associated with ruminating and grazing?

f) Does a lamb fed a high concentrate diet have increased liveweight gain compared to a lamb fed a high forage diet when both fed in confinement?
g) What are the effects of extending the adaptation period to a high concentrate diet on rumen pH, feed intake and diet digestibility and does the previous diet have carryover effects?
h) Does the provision of fibre increase concentrate intake by maintaining rumen pH and reducing the risks of acidosis whilst adapting lambs to a feedlot ration?
i) Is yard weaning advantageous for lambs to introduce them to the feedlot ration and feeding equipment?
j) Are there alternative approaches to yard weaning that are as effective at improving temperament of livestock and what are the long-term effects on adaptation to a feedlot?
k) Do shy feeders exist due to a social or nutritional issue? How many lambs that enter lamb feedlots are shy feeders and how are shy feeders best managed?
l) Are improvements in the digestibility of a diet fed to sheep related to age, animal size or rumen capacity?
m) What are the effects of processing the fibre source fed to lambs in feedlots on feed intake, diet digestibility and rumen pH? Including comparison of differing fibre quality and inclusion levels.
n) Do ruminants exposed to a prior nutritional restriction have improved efficiency of empty body gain?
o) Can CT scans be used for the precise repeat measurement of body composition in lambs?

4.2 Producer Survey

Eighty lamb producers participated in the survey, and of these responses, 59 (74%) completed the survey to provide analysable results, whereas 21 (26%) elected not to complete the survey and their responses were therefore not included in the analyses.

4.2.1 Demographics and farm characteristics

The survey respondents were located in New South Wales (60%; 35/58), Victoria (22%; 13/58), South Australia (16%; 9/58) and Western Australia (2%; 1/58). The median property size was 1257 ha (IQR 665–2313 ha) and median time operating a feedlot was 4 years (IQR 2–10 years). For respondents from low-rainfall regions (<500 mm), the median operator experience was 5 years (IQR 2–12 years); for respondents from high-rainfall regions (≥500 mm), the median operator experience was 3 years (IQR 2–5 years).

Lamb feedlots most frequently complemented cropping enterprises (69%; 41/59) and cross-bred/meat ewe and lamb enterprises (46%; 27/59; Table 5). Feedlot use was most frequently described as ‘annual’ (when pastures/crops are not available; 62%; 36/59) and ‘opportunistic’ (when grain/ lamb prices are conducive to finishing lambs on grain; 38%; 22/59). Other responses included ‘drought’ (used only in years with poor seasonal conditions; 24%; 14/59) and ‘year-round’ (feeding lambs throughout the year; 16%; 9/59).

A greater percentage of respondents from low rainfall regions (< 500 mm) used their feedlot during late autumn and winter compared with respondents in high rainfall zones (≥ 500 mm) (Figure 7). Similarly, a larger percentage of large feedlots (> 1500 lambs) used the feedlot in late autumn and winter in comparison to small feedlots (≤ 1500 lambs) (Figure 7).

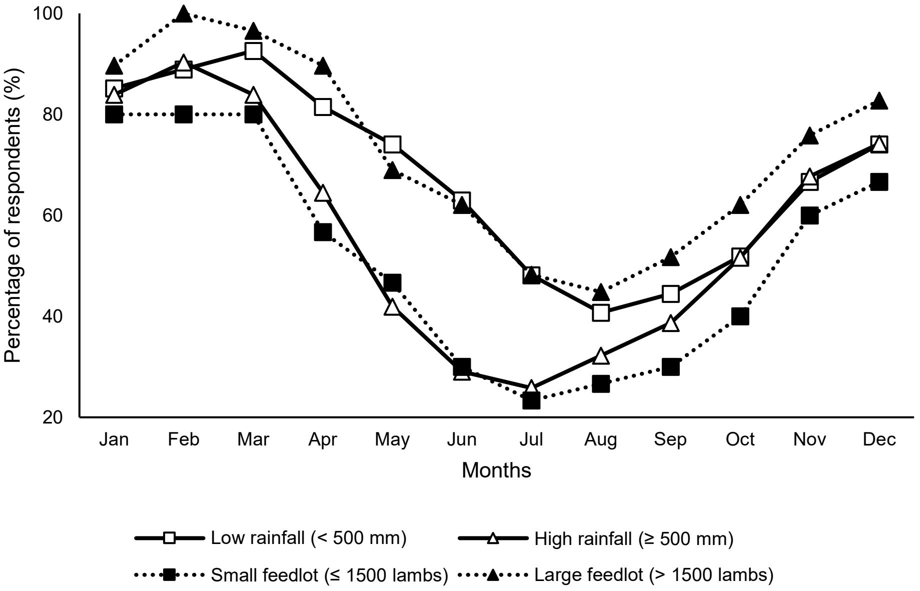


Figure 7. Typical months of feedlot operation of participants: comparison between low and high rainfall regions (solid line) and small and large feedlots (broken line).

The median number of lambs finished in an average year was 1500 (IQR 800–4000), and the median number of lambs finished for the 2019 calendar year was 1200 (IQR 450–3000). Small feedlots had a utilisation rate of 0.72 (lambs finished annually/feedlot capacity), whereas large feedlots had a utilisation rate of 3.12. The median area provided per lamb in the feedlot was 5 m^2 (IQR 3.3–8.4 m^2), and the median shaded area per lamb was 0.8 m^2 (IQR 0.3–1.8 m^2), with 76% (45/59) utilising trees to provide shade either alone or in combination with an alternative shade type (Table 5). Yards that have been specifically designed to finish lambs were constructed by 53% (31/58) of respondents (Table 5). Six (of 59) participants had local government approvals, which are required when >4000 lambs are being fed in a feedlot at any one time.

Table 5. Demographics and farm characteristics.

Characteristic	No. respondents	%
Average annual rainfall (mm)		
< 350	9	16
350 – 499	18	31
500 – 649	22	38
650 – 800	7	12
> 800	2	3
Enterprise type		
Cropping/hay/silage	41	69
Cross-bred/meat ewes and lambs	27	46
Merino ewes and cross-bred lambs	23	39
Merino ewes and merino lambs	19	32
Cattle	16	27
Only lamb feedlot	2	3
Shade type		
Trees	45	76
Artificial shade	19	32

Open shed	8	14
Aspect	3	5
None	2	3
Feedlot yard structure		
Specialist feedlot yards	31	53
Existing infrastructure	16	28
Semi-permanent yards	10	17
Indoor feedlot shed	1	2

4.2.2 Lamb description and management

A combined total of 365 370 lambs were reported as finished in feedlots in this survey in an average year. Of those, 41 620 (11%) were Merinos, 187 640 (51%) were a cross-bred lamb from a Merino ewe (first cross), 91 840 (25%) were a cross-bred lamb from a first-cross ewe (second cross), 25 420 (7%) were composites, 16 550 (5%) were Dorpers and the remaining 2300 (1%) were other breeds. For small feedlots, Merinos (36%) were the most common lambs finished, whereas for large feedlots, it was first-cross lambs (54%; Figure 8).

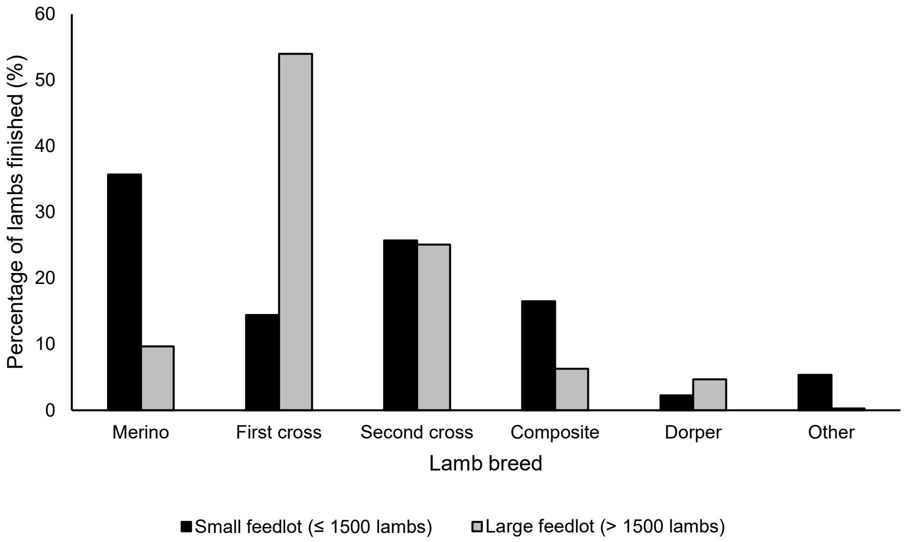


Figure 8. The percentage of lamb breeds finished: comparison between small and large feedlots.

Of the lambs finished, 156 057 (43%) were bred on the farm where feedlotting occurred, 114 255 (31%) were sourced by a direct on-farm purchase, contract or via an online sale and 95 058 (26%) were sourced from saleyards. For small feedlots, 19 821 (82%) lambs were bred on the farm where feedlotting occurred, and the remaining 4449 (18%) were sourced off–farm. Whereas in large feedlots, the majority of lambs (204 864, 60%) were sourced off farm, with 110 655 (32%) via direct purchases and 94 209 (28%) from saleyards.

The median entry age of lambs into the feedlot was 20 weeks (IQR 16–24 weeks) and entry weight was 36 kg (IQR 33–39 kg). The most common induction husbandry practices were drenching for intestinal parasites (85%; 50/59), clostridial vaccination (83%; 49/59), shearing (80%; 46/59) and drafting lambs into similar weight groups (71%; 42/59) (Table 6).

Table 6. Management of lambs in feedlots.

Characteristic	No. respondents	%
Induction practices		
Drench	50	85
Clostridial vaccination	49	83
Shearing	46	80
Draft into weight groups	42	71
Weight record	34	58
Vitamin B_{12}	30	51
Vitamin A, D & E	17	29
Crutching	10	17
Fly protection	10	17
Lice treatment	9	15
Draft into gender groups	8	14
Finishing period length (weeks)		
<6	11	19
7 – 8	19	32
9 – 10	13	22
11 – 12	7	12
>13	9	15
Target finish weight (kg)		
45 – 50	6	10
51 – 55	22	37
56 – 60	14	24
61 – 65	12	20
>65	5	8
Mob sizes		
<200	14	24
200 – 300	32	55
>300	12	21

Lambs were mostly introduced to grain prior to entering the feedlot (49/59; 83%). The median induction period for introducing lambs onto the feedlot ration was 10 days (IQR 10–14 days), and the most common length of finishing period was 7–8 weeks (Table 6). The most common finishing liveweight was between 51 and 55 kg; however, 52% (31/59) fed lambs to a liveweight greater than 55 kg (Table 6).

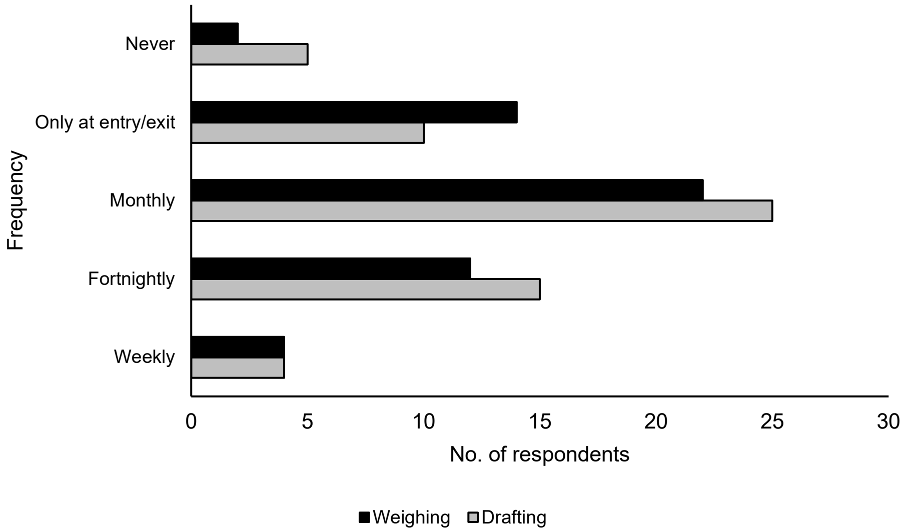


Figure 9. Frequency of weighing and drafting of lambs into new mobs.

The most common mob sizes were between 200 and 300 lambs (55%; 32/59; Table 6). The percentage of producers that weighed lambs monthly (41%; 22/54) and drafted lambs into new mobs monthly (42%; 25/59) were similar (Figure 9). The majority (63%; 37/59) of feedlot operators recorded LW gain, with electronic identification devices used by 29% (17/59) of operators. Eleven (30%) of the 37 feedlotters that recorded LW gain reported an average daily gain (ADG) for lambs between 101 and 150 g/day during the induction period, and 12 (32%) indicated an ADG of between 301 and 350 g/day in the feeding period. Six producers (16%) reported an ADG of ≤200 g/day, with one producer reporting ADG >400 g/day (Figure 10).

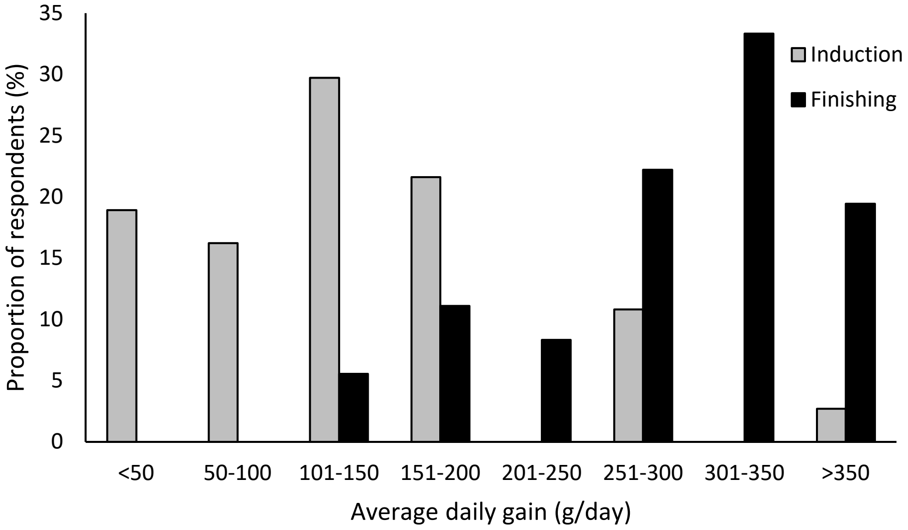


Figure 10. Lamb average daily LW gain (g/day) in induction and finishing periods.

4.2.3 Nutrition

The FCR (kg feed intake:kg LW gain) was reported by 41% (24/59) of respondents (Table 7) and does not include the induction period. The FCR was reported as 5:1 by 50% (12/24) of respondents; however, this result should not be considered reliable, as 29% (7/24) did not account for the additional intake of separately provided fibre in this calculation and 43% (10/23) did not calculate this on a DM basis. Moreover, FCR is dependent on the quality of the total ration. Nineteen producers reported FCR and feeding period ADG. The mean FCR was 5:1 and ADG was 293 g/day, resulting in a calculated daily DM intake of 1.45 kg and approximately 3.2% of the mean lamb LW.

Table 7. Responses to questions relating to lamb nutrition.

Characteristic	No. respondents	%
Feed conversion ratio (kg feed intake: kg LW gain)		
<4:1	2	8
4:1	4	17
5:1	12	50
6:1	4	17
>6:1	2	8
Grain source		
Grown on farm	26	44
Purchased off farm	23	39
Combination of both	10	17
Feed delivery system		
Self-feeders (*ad libitum* access)	38	64
Self-feeders (restricted access)	8	14
Fully automated delivery	6	10
Total mixed ration	5	8
Grain delivered in troughs	2	3
Water trough cleaning		
Daily	22	40
2-3 times per week	25	45
Weekly	7	13
Monthly	1	2

The reported median concentrate proportion of the finishing ration was 90% (IQR 80–95%), with cereal grains used as the primary component of concentrate for 76% (44/58) of producers. Commercial pellets were used by 18% (11/58) of respondents, and lupins or legumes were used by 5% (3/58). Grain/fibre that had been produced on the farm where the feedlot was located was utilised by 61% (36/59) of producers (Table 7). The quality of fibre was based on the energy density provided, and during the induction period, respondents reported the quality as ‘high’ (11/59; 19%), ‘medium’ (25/59; 42%) or ‘low’ (23/59; 39%). During the finishing period, respondents reported the quality as ‘high’ (12%; 7/59), ‘medium’ (9/59; 15%) or ‘low’ (37/59; 63%), with 6/59 (10%) of respondents not providing a fibre source. At least one component of the ration was sent for feed analysis by 68% (39/57) of respondents.

Self-feeders were used in 78% (46/59) of feedlots to deliver the concentrate component of the ration (Table 7), and for self-feeder systems, the median trough space per lamb was 10 cm (IQR 5–15 cm). The median trough space for fully automated delivery (6/59; 10%) was 7.5 cm (IQR 5–13 cm), and for total mixed rations (5/59; 8%), a median trough space of 20 cm (IQR 10–30 cm).

Commercial products (pellets, powder or lick blocks) were used to provide vitamins and minerals by 66% (39/59) of participants, whereas 22% (13/59) mixed their own, and 12% (7/59) did not provide additional vitamins and minerals. For those who provided vitamins and minerals (52/59; 88%), 34 (65%) mixed them with the ration. Water troughs were cleaned at least twice weekly by 85% (47/55) of respondents (Table 7).

4.2.4 Health

The median shy feeder percentage was 3.5% (IQR 2–5%), and 76% (45/59) of operators reported that they removed shy feeders from the feedlot. Of those producers, 58% (26/45) later reintroduced the lambs back into the feedlot. The median mortality percentage for all lambs was 1% (IQR 1–2%) and 28% (16/58) of respondents indicated they regularly conducted post-mortem examinations, with 56% of these (9/16) regularly using a veterinarian to do so. Respondents were asked to report the percentage mortality originating from frequently observed causes (Figure 11). Acidosis (49%), pneumonia (14%) and prolapses (9%) were the three conditions reported as the most common causes of mortality.

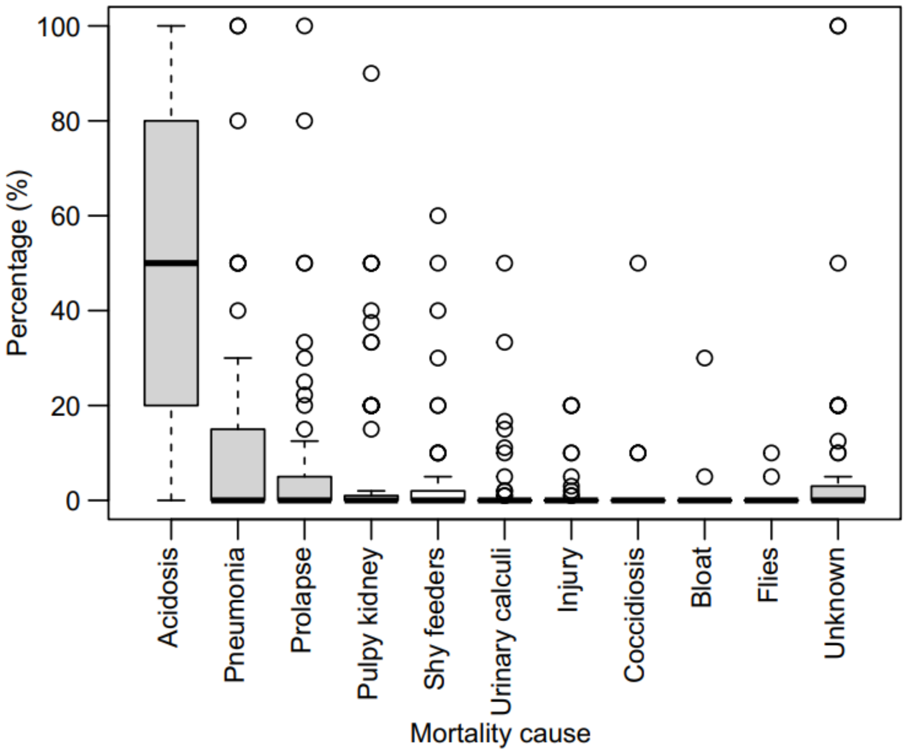


Figure 11. Mortality causes in lamb feedlots.

4.2.5 Resources and knowledge

There was a broad range of resources used for ration formulation and management of the lambs, and similarly for the design and construction of the feedlot (Figure 12). The most frequently utilised resource for nutrition and management was independent consultants (70%; 39/56), and for design and construction was the producers' own research and trials (75%; 45/56).

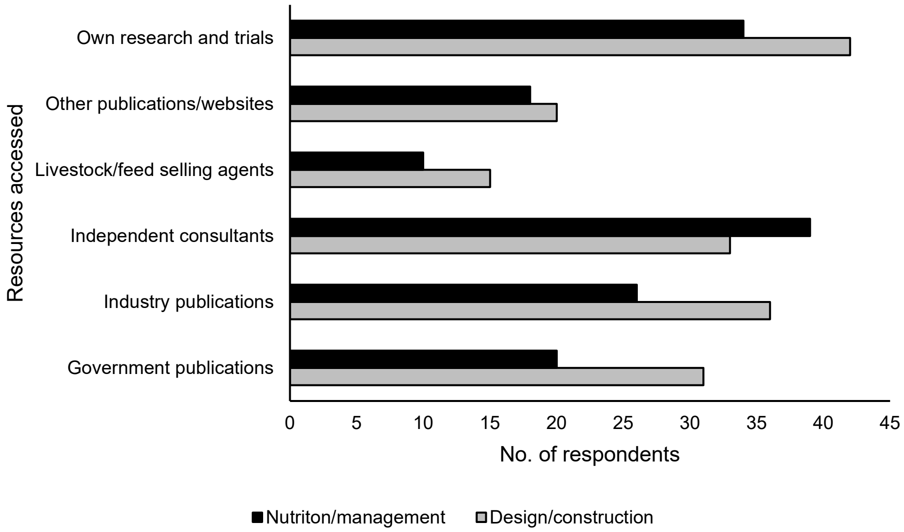


Figure 12. The resources accessed to assist with the nutrition/management of lambs and design/construction of the feedlot.

The final, open response, question asked participants what knowledge they believed was lacking that could benefit their feedlotting enterprise. Twenty (34%; 20/59) responses were collated, with seven (35%; 7/20) indicating they would likely benefit from an improved ability to predict LW gains and FCR. Other responses included health issues (notably, prevention of prolapse and pneumonia), nutrition (including the value of feed additives, use of antibiotics and best practice induction protocols) and stress (in relation to the benefits of shade and the effects of mixing mobs). Less common subjects included better ways to keep records, the value of automated feeding systems and lack of carcass feedback from abattoirs.

4.3 Monitoring lamb growth rates on commercial farms

A summary of lamb growth rates on commercial farms is presented in Table 8. Pre-weaning lamb growth rates were greater than post-weaning on all farms except one where growth rates pre- and post-weaning were very similar. On all farms the growth rate standard deviations were high. Overall, terminal breed sheep grew faster than cross-bred lambs which grew faster than Merinos.

Table 8. Survey of pre- and post-weaning lamb growth rates (g/day ± SD) on Australian commercial farms by breed.

Breed	Year	Number of lambs	Pre-weaning (g/day)	Post-weaning (g/day)
Merino	2019	618	124 ± 59	129 ± 40
Merino^A	2017	659	210 ± 47	77 ± 29
Merino^A	2018	763	252 ± 41	11 ± 36
Merino	2019	1520	292 ± 70	207 ± 91
Cross-bred	2019	1365	229 ± 93	217 ± 105
Cross-bred	2019	432	262 ± 75	210 ± 57
Cross-bred	2019	2499	330 ± 66	215 ± 80
Cross-bred	2019	336	350 ± 65	221 ± 73
Poll Dorset/White Suffolk^A	2019	692	378 ± 59	192 ± 79

Poll Dorset/White Suffolk[A]	2019	90	380 ± 61	329 ± 194
White Suffolk	2018	238	437 ± 86	382 ± 103

[A] Indicates birthweight used to calculate pre-weaning growth rate

4.4 Experiment 1: Optimising preparation and adaptation of lambs to increase feed intake and subsequently growth rate

There were no significant interactions between pre- and post-weaning treatments and the treatment effects from each period are therefore presented separately. In the pre-weaning period, there were no sex effects on liveweight or average daily gain. Growth rate of desexed male lambs was greater than female lambs (138 ± 13 v. 116 ± 13 g/day; P=0.04) between weaning and the conclusion of the post-weaning period and liveweight at the conclusion of the post-weaning period was greater for males compared with females (39.1 ± 0.4 v. 38.5 ± 0.4 kg; P=0.03). Male lambs were also heavier at the conclusion of the experiment (43.8 ± 0.4 v. 42.8 ± 0.4 kg; P=0.03); however, growth rates during the finishing period were not different between sexes. Five lambs died suddenly whilst in the feedlot; two were confirmed as caused by pneumonia and a third was suspected to be caused by pneumonia with the other two unsuitable for necropsy.

4.4.1 Pre-weaning treatment effects

In the pre-weaning period, there were no significant differences in liveweight or average daily gain due to treatment. The mean weight at lamb marking was 18.3 ± 0.4 kg and the mean weaning weight was 35.2 ± 0.4 kg. The mean pre-weaning average daily gain was 376 ± 10 g/day.

Pre-weaning treatment had significant effects on post-weaning liveweight (P<0.001; Figure 13) and average daily gain (P=0.004) to 16 days post-weaning. Lambs provided hay during the pre-weaning period lost liveweight and were lighter (-32 ± 20 g/day; 34.3 ± 0.4 kg) than lambs previously in the grain + hay (34 ± 20 g/day; 35.7 ± 0.4 kg) or grain (66 ± 20 g/day; 36.1 ± 0.4 kg) treatments; however, they were not different to control group lambs (9 ± 21 g/day; 35.0 ± 0.4 kg). Lambs previously provided grain grew faster and were heavier than both the hay treatment and control group but were not different from the grain + hay treatment.

Lambs provided hay during the pre-weaning period were lighter (37.9 ± 0.4 kg; Figure 13; P=0.02) at the conclusion of the post-weaning period than lambs previously in the grain treatment (39.3 ± 0.4 kg), with the control group (39.0 ± 0.4 kg) and grain + hay treatments (38.8 ± 0.4 kg) intermediate and not different from any other treatments. There were no effects of pre-weaning treatment on lamb growth rate during the second half of the post-weaning period (264 ± 19 g/day). Overall growth rates for the post-weaning period were lower (P=0.02) for the lambs previously provided hay pre-weaning (99 ± 15 g/day) compared to the grain treatment (146 ± 15 g/day) and control group lambs (135 ± 15 g/day). Growth rates of lambs previously provided grain + hay (126 ± 15 g/day) did not differ from any other treatments. Pre-weaning treatments had no effect on liveweight or average daily gain during the finishing period.

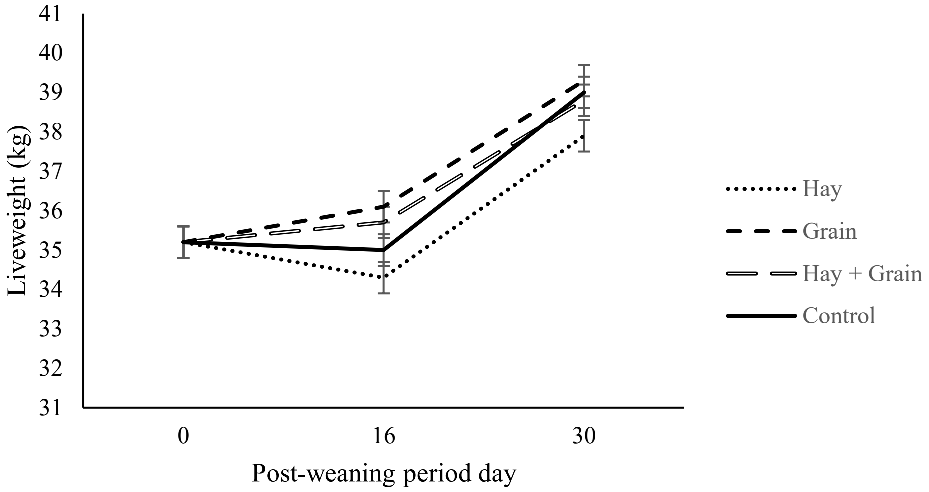


Figure 13. Effects of pre-weaning treatment on post-weaning period lamb liveweight (± SE).

4.4.2 Post-weaning treatment effects

At the commencement of the post-weaning period, lambs allocated to the supplemented pasture treatment were lighter than the unsupplemented pasture or feedlot treatments (Table 9) and weaning weight was therefore included as a covariate for subsequent analysis. Lambs in the feedlot treatment lost liveweight and were lighter at day 16 of the post-weaning period compared to the two pasture treatments (Table 9). At the conclusion of the post-weaning period, lambs in the feedlot were lighter than unsupplemented pasture lambs but not different from the supplemented pasture treatment. The unsupplemented pasture treatment grew faster than supplemented pasture lambs whereas lambs in the feedlot were not different to the two pasture treatments (Table 9). Overall average daily gain during the post-weaning period was lower for feedlot lambs (99 ± 14 g/day; $P<0.001$) compared to unsupplemented pasture (152 ± 14 g/day), whereas the supplemented pasture treatment (129 ± 14 g/day) did not differ from other treatments.

Table 9. Effects of post-weaning treatment on mean lamb liveweight (LW; kg ± SE) and average daily gain (ADG; g/day ± SE) from weaning until experiment conclusion. Different superscripts at each timepoint indicate treatment means differed significantly (P<0.05).

	Feedlot		Grazing pasture with no supplements		Grazing pasture with supplements	
	LW	ADG	LW	ADG	LW	ADG
Post-weaning period						
Day 0	35.4 ± 0.5^{b}	-	35.5 ± 0.5^{b}	-	34.3 ± 0.5^{a}	-
Day 16	34.6 ± 0.3^{a}	-16 ± 18^{a}	35.6 ± 0.3^{b}	32 ± 18^{b}	35.6 ± 0.3^{b}	42 ± 18^{b}
Day 30	38.0 ± 0.4^{a}	261 ± 23^{ab}	39.5 ± 0.4^{b}	296 ± 23^{a}	38.8 ± 0.4^{ab}	236 ± 23^{b}
Finishing period						
Day 16	41.4 ± 0.6	210 ± 31^{a}	40.9 ± 0.6	92 ± 31^{b}	41.0 ± 0.6	131 ± 31^{ab}
Day 39	43.5 ± 0.7	110 ± 19	42.7 ± 0.7	70 ± 19	43.8 ± 0.7	115 ± 19

Overall growth rates for the finishing period were lower ($P=0.003$) for the previously unsupplemented pasture treatment (79 ± 16 g/day) compared to the feedlot post-weaning treatment (148 ± 16 g/day), whereas the supplemented pasture treatment (127 ± 16 g/day) was not different to any other treatment. At day 16, lambs that had been in the feedlot during the post-weaning period had grown faster than lambs from the unsupplemented pasture treatment, and lambs in the supplemented pasture treatment were not different to other treatments (Table 9). From day 16 to the conclusion of the experiment, there were no differences in average daily gain between the treatments. Liveweight at the conclusion of the finishing period was not affected by post-weaning treatment (Table 9).

4.4.3 Feed intake

Nutritive values of diet components during the pre- and post-weaning periods and feedlot phase are presented in Table 10. There were no differences in grain or hay dry matter (DM) intake between treatments during the pre-weaning period with a mean grain DM intake of 93 ± 17 g/head/day and a mean hay DM intake of 118 ± 23 g/head/day. Supplement DM intake (319 ± 68 g/head/day) whilst grazing pasture in the post-weaning period was not affected by supplementation status of lambs pre-weaning. Dry matter intake of grain by lambs weaned directly into the feedlot following the induction period was not affected by pre-weaning treatment with lambs consuming mean 0.96 ± 0.02 kg/head/day during the post-weaning period and mean 1.53 ± 0.03 kg/head/day during the first 16 days of the finishing period whilst lambs from the pasture treatments were being inducted.

Table 10. Nutritive values of mixed grain diet, lucerne hay and straw provided to lambs whilst in the feedlot.

	Grain	Lucerne Hay[A]	Lucerne Hay[B]	Straw
Neutral Detergent Fibre (%)	21	53	43	82
Acid Detergent Fibre (%)	10	38	31	50
Crude Protein (%)	18	15.1	18.8	3.7
DOMD[C] (%)	82	56	65	43
M/D[D] (MJ ME/kg DM)	12.9	8.4	10.1	5.7

[A] Pre-weaning period and post-weaning period feedlot induction
[B] Finishing period feedlot induction
[C] Dry organic matter digestibility
[D] Metabolisable energy density

Pre-weaning treatment had no effects on grain DM intake in the finishing period and there were no interactions with post-weaning treatment. Lambs weaned directly into the feedlot had greater grain DM intake than unsupplemented pasture lambs in the finishing period with supplemented pasture lambs not different to other post-weaning treatments (Table 11).

Lucerne hay DM intake during the induction period to the feedlot was greater for both supplemented and unsupplemented lambs weaned onto pasture and entering the feedlot at an older age in comparison to lambs weaned directly into the feedlot (Table 11). There were no effects of pre- or post-weaning treatment on straw intake in the feedlot with lambs consuming a mean DM intake of 0.48 ± 0.02 kg/head/day.

Table 11. Effects of post-weaning treatment on mean lamb grain and hay/straw dry matter intake (g/head/day ± SE) for the induction periods (1 December; weaned into feedlot, and 30 December; pasture treatments) and the final 23 days of the experiment. Different superscripts at each timepoint indicate treatment means differed significantly (P<0.05).

	Induction period		Finishing Day 17-39	
	Grain	Hay/Straw^{A}	Grain	Hay/Straw^{A}
Feedlot	0.40	1.58 ± 0.09^{a}	1.55 ± 0.07^{a}	0.49 ± 0.04
Grazing pasture with no supplements	0.40	1.97 ± 0.09^{b}	1.27 ± 0.07^{b}	0.45 ± 0.04
Grazing pasture with supplements	0.40	1.94 ± 0.09^{b}	1.50 ± 0.07^{ab}	0.50 ± 0.04

^{A}Lucerne hay provided for induction periods and barley straw for ad libitum feeding

4.4.4 CT scans

The average liveweight and ADG of lambs CT scanned did not differ from those not scanned during the experiment. Pre-weaning treatment had no effect on stomach volume for lambs that were weaned directly into the feedlot. Stomach volume at feedlot entry was greater in older lambs from the two pasture treatments (7.4 ± 0.4 L) that were CT scanned 32 days later than lambs that were weaned directly into the feedlot (4.4 ± 0.4 L; P<0.001). The stomach volumes of supplemented and unsupplemented pasture treatments did not differ. At the conclusion of the experiment, stomach volume was 8.0 ± 0.2 L and with no treatment or sex effects.

There were no treatment or sex effects on FFEBW at feedlot entry (30.0 ± 0.5 kg) or at the conclusion of the experiment (33.4 ± 0.5 kg). Empty body fat weight was 5.4 ± 0.2 kg at feedlot entry with males containing less fat than females (5.1 ± 0.3 v. 5.8 ± 0.3 kg; P=0.012). Empty body lean weight was 21.3 ± 0.2 kg at feedlot entry and male lambs contained increased lean in comparison to females (21.9 ± 0.3 v. 20.7 ± 0.3 kg; P=0.002). At the conclusion of the experiment, empty body fat weight was 7.7 ± 0.3 kg with no sex effects and lambs had an empty body lean weight of 22.3 ± 0.3 kg with male lambs containing more lean than females (22.9 ± 0.5 v. 21.8 ± 0.4 kg; P=0.026). There were no differences in empty body, fat or lean ADG between sex or pre- and post-weaning treatments from entry into the feedlot until the conclusion of the experiment, and the rates of gain were lower than predicted by the calculations from feeding standards (Table 12).

Table 12. Comparison of fleece free empty body, fat and lean average daily gain (ADG; g/day ± SE) from feedlot entry until experiment conclusion with predicted values based upon lamb characteristics, diet composition and intake (CSIRO 2007).

	Predicted means	CSIRO (2007)^{A}
Fleece free empty body ADG	73 ± 8	207
Fat ADG	46 ± 3	99
Lean ADG	23 ± 6	107

^{A}Calculations based upon mixed grain intake only, excludes hay/straw intake

4.5 Experiment 2: Level of feeding and stage of maturity affects diet digestibility and protein and fat deposition in cross-bred lambs

Liveweight data in Figure 14 and 15 are presented as raw (unadjusted) means (Figure 14) and values (Figure 15) by level of main effect within timepoint. Body composition, energy balance and diet digestibility results (Table 3, Tables 12 to 14 and Figure 16) are presented as predicted means ± SE. There were no significant interactions between the first and second feeding period and the treatment effects from each period are therefore presented separately.

Mean LW of lambs at the commencement of P1 was 31.8 ± 0.3 kg and did not differ between treatments. The mean LW of H1 lambs was greater than L1 lambs at the conclusion of P1 (44.1 ± 0.6 v. 36.2 ± 0.6 kg; P<0.001), the commencement of P2 (41.8 ± 0.4 v. 39.2 ± 0.4 kg; P<0.001) and the conclusion of P2 (49.2 ± 0.5 v. 46.8 ± 0.5 kg; P<0.001; Figure 14). Mean daily ME intake was 9.5 ± 0.03 and 15.3 ± 0.03 MJ ME/d and mean DM intake was 847 ± 3 and 1357 ± 3 g/d for L1 and H1 lambs respectively. Dry matter intake as a percentage of LW for L1 and H1 treatments was respectively 2.5 and 3.6%.

4.5.1 Liveweight and intake

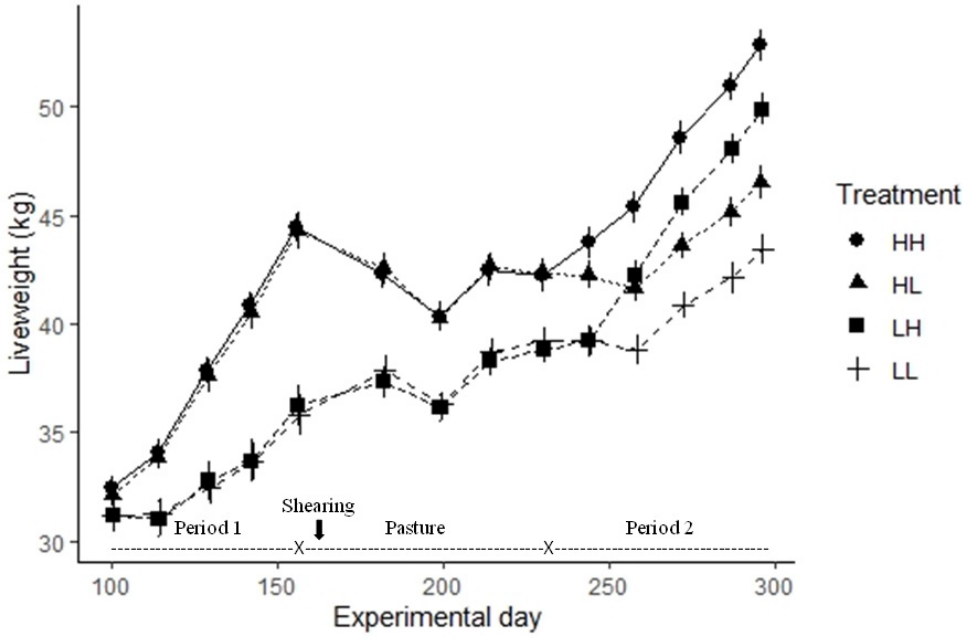


Figure 14. Mean lamb liveweight (±SE) from the commencement of feeding period one until the conclusion of feeding period two for H (high) and L (low) feeding levels during each period. The first letter of treatment indicates feeding period one and second letter indicates feeding period two.

Mean LW of lambs at the commencement of P2 was 40.5 ± 0.3 kg and did not differ between P2 treatments (due to the reallocation of half of the lambs to different treatments). The mean LW of H2 lambs was greater than L2 lambs at the conclusion of P2 (51.3 ± 0.5 v. 44.7 ± 0.5 kg; P<0.001; Figure 14). Including hay provided during the first week of P2, mean daily ME intake was 12.0 ± 0.01 and 15.2 ± 0.01 MJ ME/d and mean DM intake was 1031 ± 1 and 1491 ± 1 g/d for L2 and H2 lambs respectively. Dry matter intake as a percentage of LW were similar to the targeted feeding level at 2.4% for L2 and 3.3% for H2 treatments.

4.5.2 Empty body composition and gain

Lambs allocated to H1 or L1 did not differ in FFEBW or composition of the empty body (fat, lean and bone mass) at the commencement of P1. The H1 treatment resulted in higher rates of gain in FFEBW, fat, lean and bone mass than L1 lambs in P1 (Table 13). Lambs allocated to H1 had a greater FFEBW and mass of empty body components at the commencement of P2 compared to L1 despite the pasture phase between P1 and P2. The pasture phase resulted in a loss in FFEBW, empty body fat and lean mass for H1 lambs (Table 13). Lambs in L1 lost less fat (P<0.001) than H1 lambs but gained lean mass resulting in a net FFEBW gain in the pasture phase. Lambs allocated to H1 still had greater FFEBW and mass of fat, lean and bone compared with L1 lambs at the conclusion of P2. There were no differences in rate of FFEBW, fat or lean gain during P2 due to P1 feeding level (Table 13).

Table 13. Empty body component mass and rate of gain means (± SE) across feeding period 1 and feeding period 2 for lambs that were allocated to high or low feeding level treatments in feeding period 1. Different superscripts at each timepoint indicate treatment means differed significantly (P<0.05).

Treatment[A]	FFEBW[B] (kg)	FFEBW[B] gain (g/day)	Fat (kg)	Fat gain (g/day)	Lean (kg)	Lean gain (g/day)	Bone (kg)	Bone gain (g/day)
Feeding period 1								
Start	25.9 ± 0.3	-	4.5 ± 0.1	-	18.0 ± 0.2	-	3.4 ± 0.04	-
Finish								
Low	29.9 ± 0.5^a	72.8 ± 8.2^a	6.4 ± 0.2^a	34.5 ± 3.3^a	19.7 ± 0.3^a	28.6 ± 5.1^a	3.8 ± 0.1^a	9.1 ± 0.9^a
High	37.0 ± 0.4^b	197.7 ± 7.8^b	9.6 ± 0.2^b	90.5 ± 3.1^b	23.2 ± 0.3^b	92.2 ± 4.9^b	4.1 ± 0.1^b	13.8 ± 0.9^b
Feeding period 2								
Start								
Low	31.2 ± 0.3^a	19.4 ± 5.1^a	5.9 ± 0.2^a	-13.8 ± 2.2^a	21.9 ± 0.2^a	31.1 ± 3.2^a	4.0 ± 0.1^a	1.3 ± 0.4
High	33.5 ± 0.3^b	-46.5 ± 5.0^b	6.3 ± 0.2^b	-40.1 ± 2.2^b	22.7 ± 0.2^b	-6.1 ± 3.1^b	4.2 ± 0.1^b	
Finish								
Low	39.6 ± 0.4^a	125.1 ± 4.0	11.1 ± 0.3^a	84.2 ± 2.1	24.1 ± 0.2^a	33.9 ± 2.5	4.4 ± 0.1^a	6.3 ± 0.5
High	41.6 ± 0.4^b		12.1 ± 0.3^b		24.9 ± 0.2^b		4.6 ± 0.1^b	

[A] Low, low level of feeding (dry matter intake 2.5% of liveweight); High, high level of feeding (dry matter intake 3.6% of liveweight)

[B] Fleece free empty body weight

Lambs in H2 had greater rates of gain in FFEBW and empty body components than L2 lambs during P2 resulting in greater mass of FFEBW and empty body fat and lean mass at the conclusion of P2 (Table 14).

Table 14. Empty body component mass and rate of gain means (± SE) for second feeding period treatments. Different superscripts at each timepoint indicate treatment means differed significantly (P<0.05).

Treatment[A]	FFEBW[B] (kg)	FFEBW[B] gain (g/day)	Fat (kg)	Fat gain (g/day)	Lean (kg)	Lean gain (g/day)	Bone (kg)	Bone gain (g/day)
Start	32.4 ± 0.2	-	6.1 ± 0.1	-	22.3 ± 0.2	-	4.1 ± 0.04	-
Finish								
Low	37.5 ± 0.4^a	73.9 ± 5.3^a	9.9 ± 0.3^a	57.8 ± 2.8^a	23.1 ± 0.2^a	9.8 ± 3.4^a	4.5 ± 0.04	5.0 ± 0.7^a
High	43.8 ± 0.4^b	176.3 ± 5.4^b	13.3 ± 0.3^b	110.7 ± 2.8^b	25.9 ± 0.2^b	57.9 ± 3.3^b		7.7 ± 0.7^b

[A] Low, low level of feeding (dry matter intake 2.4% of liveweight); High, high level of feeding (dry matter intake 3.3% of liveweight)

[B] Fleece free empty body weight

For any rate of fleece-free empty body gain, P1 lambs deposited less fat in the empty body than did P2 lambs (Figure 15). Empty body fat gain as a proportion of FFEBW gain was greater for lambs in P2 than P1 (0.70 v. 0.52; P<0.001).

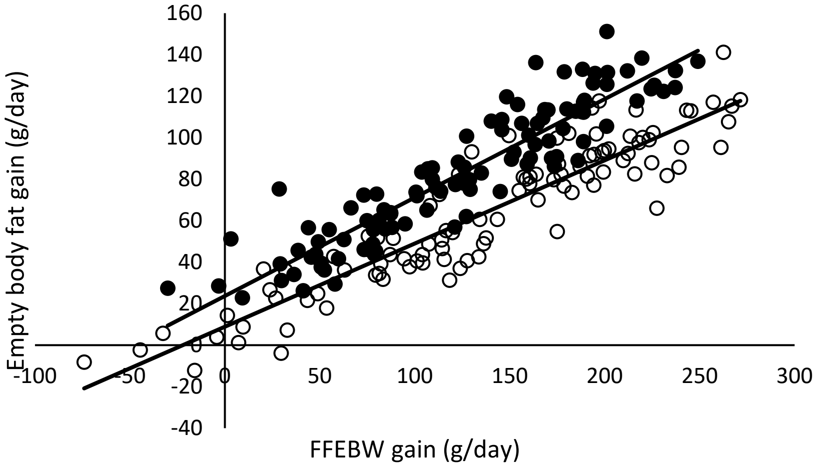


Figure 15. Relationship between rate of empty body fat gain (g/day) and total empty body gain (g/day) for lambs from low and high levels of intake during feeding period one (P1: hollow symbols) and feeding period two (P2: solid symbols). P1; y = 0.401x + 8.8903, r^2 = 0.85; P2; y = 0.4745x + 23.704, r^2 = 0.85.

The protein gain determined using CT scans for both feeding levels in both periods was less than anticipated based on calculations from CSIRO (2007) (Table 15). The anticipated fat gain corresponded reasonably well between CSIRO (2007) calculations and CT scan results with the exception of H2 lambs where fat gain was underestimated by CSIRO (2007). The proportion of fat in retained energy was greater for all treatments than anticipated from CSIRO (2007) equations, and particularly for L lambs. The proportion of fat in retained energy was greater for L2 lambs than H2 lambs (Table 15, P<0.001).

The percentage of fat in the fleece free empty body of all lambs was 17.6 ± 0.4% at the commencement of P1 and increased to 23.9 ± 0.4% at the conclusion of P1 (P<0.001). Fat percentage at the conclusion of P1 was greater for H1 lambs in comparison to L1 lambs (25.9 ± 0.5 v. 21.4 ± 0.5%; P<0.001; Figure 16). The fat percentage of all lambs decreased from 23.9 ± 0.4% at the conclusion of P1 to 18.7 ± 0.4% at the commencement of P2 (P<0.001). At the commencement of P2, previously H1 lambs maintained a greater percentage of fat in comparison to previously L1 lambs (19.8 ± 0.6 v. 17.3 ± 0.6%; P=0.001; Figure 16). At the commencement of P2, there were no differences due to P2 treatment due to the reallocation of half of the lambs to different treatments. The empty body fat percentage of all lambs increased from 18.7 ± 0.4% at the start of P2 to 28.2 ± 0.4% at the conclusion of P2 (P<0.001). No differences were detected at in empty body fat percentage at the end of P2 due to treatment in P1. The empty body fat percentage of H2 lambs was greater than L2 lambs (30.3 ± 0.6% v. 26.2 ± 0.6%; P<0.001; Figure 16).

Table 15. Energy balance mean values using calculations by CSIRO (2007) and comparison to mean values (± SE) using CT scan data. Different superscripts at each timepoint indicate treatment means differed significantly (P<0.05).

Treatment[A]	Energy value fat gain (MJ/day)[B]	Energy value protein gain (MJ/day)[C]	Proportion fat in retained energy (%)	Efficiency of energy utilisation for gain[D]	CSIRO (2007)				
					Maintenance energy requirement (MJ/day)	Available energy for gain (MJ/day)	Energy value fat gain (MJ/day)[B]	Energy value protein gain (MJ/day)[C]	Proportion fat in retained energy (%)
Feeding period 1									
Low	1.35 ± 0.12^{a}	0.13 ± 0.02^{a}	89.8 ± 0.6	0.41	5.91	3.59	1.58	0.31	83.6
High	3.56 ± 0.13^{b}	0.44 ± 0.02^{b}		0.47	6.82	8.48	3.86	0.63	86.0
Feeding period 2									
Low	2.27 ± 0.11^{a}	0.05 ± 0.02^{a}	97.1 ± 0.4^{a}	0.48	7.14	4.86	2.22	0.28	88.8
High	4.35 ± 0.11^{b}	0.27 ± 0.02^{b}	94.0 ± 0.4^{b}	0.62	7.70	7.50	3.26	0.39	89.3

[A] Low, low level of feeding; High, high level of feeding.

[B] Fat energy density: 39.3 MJ/kg (CSIRO 2007)

[C] Protein energy density: 23.6 MJ/kg (CSIRO 2007), protein gain: 20% of lean tissue gain (Dougherty et al. 2020)

[D] The proportion of retained energy from available energy for gain calculated by CSIRO (2007)

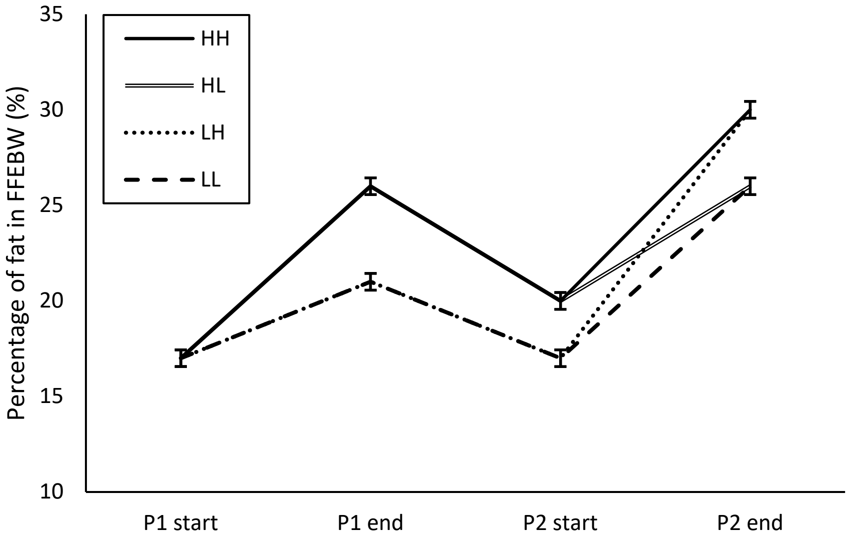


Figure 16. Mean fat percentage of fleece free empty body weight (FFEBW) from the commencement of feeding period one (P1) until the conclusion of feeding period two (P2) for high (H) and low (L) feeding levels during each period. Treatment first letter indicates feeding period one and second letter indicates feeding period two.

Desexed male lambs had greater FFEBW (P=0.001) and lean tissue mass (P<0.001) at the commencement of P1 and females had greater fat mass (P=0.01) at the conclusion of P2. Sex had no other significant effects throughout the experiment. Sire type had effects on lean tissue mass (P<0.001) at the conclusion of P1 and P2 and commencement of P2 but no other effects of sire were detected.

4.5.3 Stomach volume and mass

Mean reticulo-rumen, omasum and abomasum (stomach) volume did not differ between treatments within feeding periods but differed between all CT scan timepoints (P<0.001). At the commencement of P1 the mean stomach volume was 5.1 ± 0.2 L and at the conclusion was 5.5 ± 0.2 L. At the commencement of P2 the mean stomach volume was 7.6 ± 0.1 L and at the conclusion was 6.1 ± 0.1 L.

The weight of stomach contents from 48 lambs at the commencement and conclusion of each feeding period was described by the equation y=0.9372×stomach volume (L)-0.3577 with an r^2 of 0.93. No differences were detected for the proportion of particulate (22.2 ± 2.1%) and liquid (73.1 ± 2.0%) content of the stomach between treatments or feeding periods. No differences were detected for gas content of the stomach between treatments within feeding period; however, gas content was lower at the commencement of both feeding periods in comparison to the conclusion of both feeding periods (2.5 ± 1.0 v. 7.0 ± 1.0%; P<0.001).

4.5.4 Diet digestibility

The mean LW of the ten lambs used to determine diet digestibility was 30.5 ± 1.1 kg at the commencement of the first collection period and 40.1 ± 1.0 kg at the commencement of the second collection period. Dry matter intake was for L and H intake treatments respectively 0.84 ± 0.00 and

1.38 ± 0.02 kg DM/day in the first feeding period and 1.02 ± 0.00 and 1.57 ± 0.02 kg DM/day in the second feeding period.

Diet digestibility in the first collection period did not differ significantly between the high and low feeding levels (Table 3). Mean diet DM, OMD and GE digestibility was greater ($P<0.05$) in the first collection period compared to the second collection period. Crude protein and NDF digestibility did not differ significantly between collection periods; however, ADF digestibility was greater ($P<0.05$) in the second collection period. The low feeding level in the second collection period had greater DM, OMD, CP and GE digestibility compared to the high feeding level, with no differences in NDF or ADF digestibility (Table 3).

4.6 Experiment 3: The effects of diet composition and grazing on the rate of lean and fat deposition in composite lambs

4.6.1 Liveweight and empty body composition

At the commencement of the experimental period (following the adaptation period) the lambs fed ration 2 had a greater liveweight than the lambs on the lucerne pasture with ration 1 not significantly different from either treatment (Table 16). The stomach volume was greater for lambs in the feedlot fed the pelleted rations than lambs on the lucerne pasture at both experiment commencement and conclusion (Tables 16 and 17). Viscera lean mass was greater for lambs fed ration 2 than both ration 1 and the lucerne pasture lambs. Fleece free empty body weight, fat mass and NVEB lean mass were not significantly different between treatments at the commencement of the experimental period (Table 16).

Table 16. Liveweight, stomach volume and empty body component mass treatment means (± SE) at start of experimental period. Different superscripts indicate treatment means differed significantly ($P<0.05$).

	Ration 1	Ration 2	Lucerne
Liveweight (kg)	43.5 ± 0.8^{ab}	43.9 ± 0.8^{a}	41.1 ± 0.8^{b}
Stomach volume (L)	5.1 ± 0.2^{a}	5.1 ± 0.2^{a}	3.5 ± 0.2^{b}
FFEBW (kg)	36.3 ± 0.8	36.8 ± 0.8	35.6 ± 0.8
Fat mass (kg)	8.9 ± 0.5	8.6 ± 0.5	8.8 ± 0.5
Lean mass (kg)	23.3 ± 0.4	24.1 ± 0.4	22.6 ± 0.4
NVEB lean mass (kg)	18.1 ± 0.4	18.5 ± 0.4	17.6 ± 0.4
Viscera lean mass (kg)	5.2 ± 0.1^{b}	5.6 ± 0.1^{a}	5.0 ± 0.1^{b}

Average daily liveweight gain was not different between treatments; however, lambs fed ration 1 had a greater liveweight than lambs on the lucerne pasture at the end of the experiment (Table 17). Lambs fed ration 2 did not have a different liveweight to either lambs fed ration 1 or the lucerne pasture treatments. Empty body average daily gain was greater for lambs fed ration 1 compared to ration 2 and the lucerne pasture; although, there was no difference in empty body weight between treatments.

Lambs in the feedlot deposited significantly more fat each day compared to lambs on pasture and lambs fed ration 1 had a greater fat mass than lambs on pasture at the end of the experiment (Table 17). Fat mass of lambs fed ration 2 was not different to ration 1 or lambs on lucerne pasture.

Total lean mass and NVEB lean mass did not differ between treatments; however, lambs on the lucerne pasture had an increased viscera lean mass in comparison to lambs fed ration 1. Lambs fed ration 2 did not have a different viscera lean mass to lucerne pasture lambs or ration 1 fed lambs. The average daily lean gain of lucerne pasture fed lambs was greater than ration 2 lambs with ration 1 not different from other treatments. Lambs on the lucerne pasture deposited more lean each day in the viscera than other treatments. There were no differences in NVEB lean average daily gain between treatments (Table 17).

Table 17. Liveweight, stomach volume and empty body component mass (kg) and rate of gain (g/day) treatment means (± SE) at end of experimental period. Different superscripts indicate treatment means differed significantly (P<0.05).

	Ration 1		Ration 2		Lucerne	
	g/day	kg	g/day	kg	g/day	kg
Liveweight	205 ± 16	51.9 ± 1.1^{a}	152 ± 16	50.1 ± 1.1^{ab}	171 ± 16	48.1 ± 1.1^{b}
Stomach volume (L)	4.8 ± 0.2^{a}		4.6 ± 0.2^{a}		3.8 ± 0.2^{b}	
Empty body weight	203 ± 15^{a}	44.6 ± 1.0	152 ± 15^{b}	43.0 ± 1.0	150 ± 15^{b}	41.8 ± 1.0
Fat mass	141 ± 9^{a}	14.7 ± 0.7^{a}	118 ± 9^{a}	13.4 ± 0.7^{ab}	83 ± 9^{b}	12.2 ± 0.7^{b}
Lean mass	54 ± 9^{ab}	25.5 ± 0.5	31 ± 9^{b}	25.3 ± 0.5	60 ± 9^{a}	25.0 ± 0.5
NVEB lean mass	52 ± 7	20.2 ± 0.5	36 ± 7	20.0 ± 0.5	42 ± 7	19.3 ± 0.5
Viscera lean mass	2 ± 3^{b}	5.3 ± 0.1^{b}	-5 ± 3^{b}	5.4 ± 0.1^{ab}	18 ± 3^{a}	5.7 ± 0.1^{a}

There were no differences between treatments for the daily deposition of fat, viscera lean or NVEB lean for every unit of metabolisable energy intake for lambs fed in the feedlot (Figure 17).

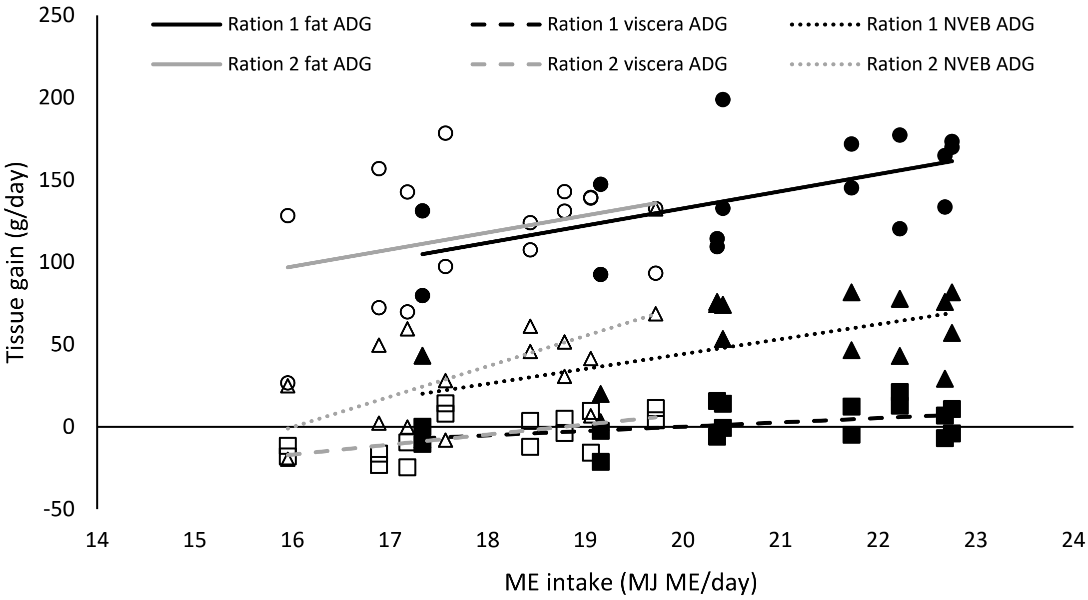


Figure 17. Average daily tissue gain of individual animals by metabolisable energy (ME) intake. Solid symbols represent ration 1 and hollow symbols represent ration 2. Symbol shapes illustrate fat gain (●), fat-free empty body lean gain (▲) and viscera lean gain (■).

4.6.2 Feed intake

Mean DM and pellet intake was greater for lambs fed ration 1 in the feedlot in comparison to ration 2 (Table 18). Neutral detergent fibre intake was not different between the rations; however, acid detergent fibre intake was greater for ration 2. Crude protein and metabolisable energy intake per head per day was greater for ration 1 (Table 18).

Table 18. Dry matter (DM) and metabolisable energy (ME) mean intake for treatments in the feedlot during the experimental period. Different superscripts indicate treatment means differed significantly (P<0.05).

	Ration 1	Ration 2
DM intake (kg/head/day)	1.72 ± 0.03^a	1.51 ± 0.02^b
Pellet DM intake (kg/head/day)	1.72 ± 0.03^a	1.29 ± 0.03^b
Hay DM intake (kg/head/day)	-	0.23 ± 0.01
NDF intake (% DM intake)	27.5 ± 0.0	27.9 ± 0.3
ADF intake (% DM intake)	11.0 ± 0.0^b	12.3 ± 0.4^a
CP intake (% DM intake)	17.7 ± 0.0^a	15.1 ± 0.5^b
ME intake (MJ ME/head/day)	20.8 ± 0.5^a	18.0 ± 0.3^b

4.6.3 Comparison of CT scans with slaughter data

The estimation of carcass weight using liveweight, stomach volume, CT scan derived viscera tissue weights, estimated weight of fleece and estimated weight of head and feed based upon liveweight showed general agreement with slaughter data (Figure 18). Both post-slaughter DEXA scans and live animal CT scan derived proportions of fat and lean in the carcass demonstrated general agreement (Figure 19).

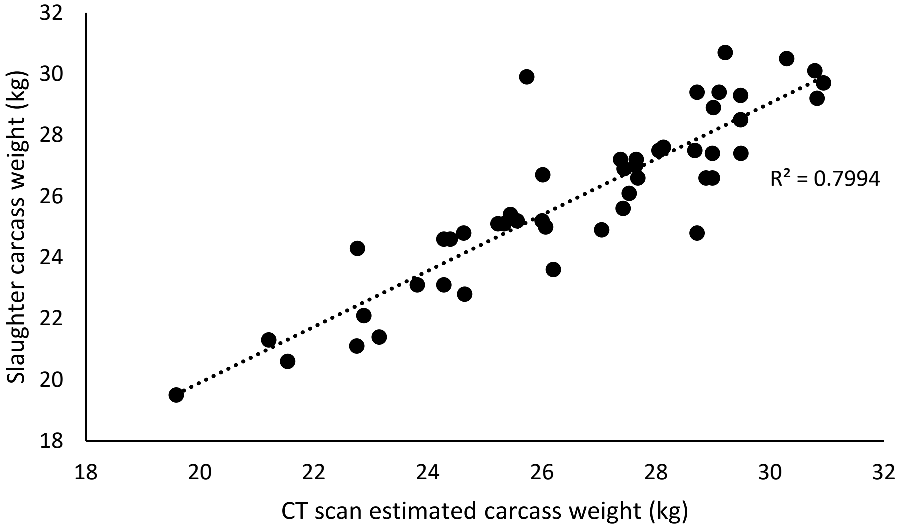


Figure 18. Comparison of CT scan estimated carcass weight and carcass weight determined by slaughter.

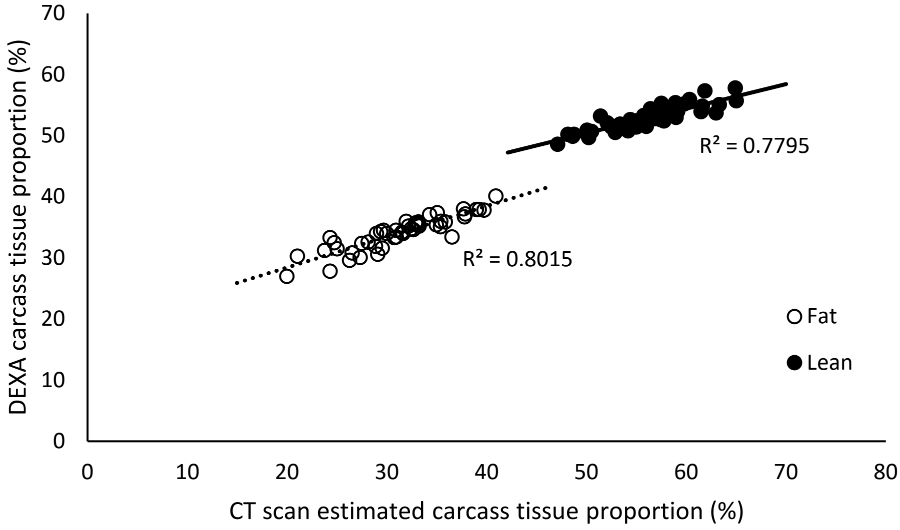


Figure 19. Comparison of the CT scan estimated proportion of fat and lean tissue in the carcass and tissue proportions determined by DEXA scans at slaughter.

4.7 Modelling lamb growth

Observed values for traits at the commencement of each feeding period compared in this study are shown in Table 19.

Table 19. Mean values (± SD) for feeding period commencement body compositional mass for each treatment within feeding period and estimated rate of greasy fleece gain

	Feeding period one		Feeding period two	
	Low	High	Low	High
FFLWT^A (kg)	29.4 ± 2.7	31.2 ± 2.2	39.4 ± 2.6	38.8 ± 3.1
Fat (kg)	4.0 ± 0.7	4.5 ± 0.6	5.4 ± 1.4	5.6 ± 1.0
Lean (kg)	21.3 ± 1.7	22.5 ± 1.8	27.0 ± 1.7	26.8 ± 2.5
Viscera lean (kg)	5.1 ± 0.5	5.1 ± 0.5	5.5 ± 0.3	5.6 ± 0.5
NVEB^B lean (kg)	16.2 ± 1.2	17.4 ± 1.5	21.5 ± 1.6	21.2 ± 2.1
Gut fill (kg)	4.2 ± 1.0	4.2 ± 0.8	7.0 ± 1.3	6.5 ± 1.1
Greasy fleece gain (g/day)	6.4 ± 0.1	10.3 ± 0.3	11.3 ± 0.1	14.3 ± 0.1

[A] Fleece free liveweight

[B] Fat-free non-viscera empty body

4.7.1 Accuracy of prediction by treatment

The data for the following comparison is shown in Table 20. Fat gain was underestimated for H2 lambs but overestimated for all other treatments by the CSIRO (2007) model. The predicted rates of fat gain by the CSIRO (2007) model showed the largest mean bias and RMSPE for L1 and H2 lambs (Table 2). Over 50% of the error by the CSIRO (2007) model for fat gain was attributed to random error for all treatments except H2 when 93.1% was attributed to overall bias. The Oddy et al. (2022) model underestimated fat gain for all treatments and to the greatest extent for H2 lambs. Over 50% of the prediction error by the Oddy et al. (2022) model was attributed to overall bias for all treatments except L1 (30.7%; Table 20).

Table 20: Observed and predicted mean rates of empty body gain and weight of gut fill with coefficient of variation (CV), mean bias, RMSPE[A] and error decomposition. Observed values calculated by CT scans and simulated values from models described by CSIRO (2007) and Oddy et al. (2022).

	Observed mean	CV of observations	Predicted mean		Mean bias (% obs mean)		RMSPE[A] (% obs mean)		Error decomposition (% MSPE[B])					
									Overall bias		Slope bias		Random error	
			Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO
Fat gain (g/day)														
P1 Low	30.3	23.2	26.8	36.1	11.6	-19.5	20.8	28.2	30.7	47.1	17.7	0.03	51.6	52.9
P1 High	81.8	10.3	70.6	86.3	13.8	-5.5	17.1	12.3	64.6	20.1	3.9	26.5	31.5	53.3
P2 Low	53.2	13.3	39.2	55.3	26.3	-3.9	28.3	14.2	86.5	7.7	1.5	21.2	12.0	71.1
P2 High	97.1	8.0	59.7	74.6	38.6	23.2	39.3	24.0	96.7	93.1	0.03	2.0	3.3	4.9
Lean gain (g/day)														
P1 Low	44.7	34.8	34.4	50.9	22.8	-13.9	40.1	33.8	32.7	16.7	12.0	4.1	55.3	79.1
P1 High	97.3	20.9	95.0	90.9	2.3	6.5	16.4	17.6	2.0	13.7	0.9	7.6	97.1	78.7
P2 Low	17.0	43.9	43.8	44.4	-158.2	-161.8	171.4	164.4	85.5	97.0	9.0	0.03	5.5	3.0
P2 High	66.1	14.7	69.4	56.5	-5.0	14.5	18.4	19.3	7.2	56.1	53.0	2.2	40.0	41.7
FFEBW[C] gain (g/day)														
P1 Low	74.9	28.0	61.2	87.0	18.3	-16.2	29.0	28.7	40.0	31.4	2.3	1.1	57.6	67.5
P1 High	179.1	11.8	165.6	177.3	7.5	1.1	10.6	8.4	50.9	1.5	12.1	34.9	37.0	63.6
P2 Low	70.2	13.3	83.0	99.7	-18.2	-42.0	25.3	43.5	52.2	93.5	23.7	0.4	24.1	6.1
P2 High	163.2	9.6	129.0	131.1	21.0	19.7	22.8	20.9	84.5	88.2	4.7	0.2	10.8	11.6
Liveweight gain (g/day)														
P1 Low	89.7	23.6	77.5	96.5	13.6	-7.7	34.4	19.8	15.5	15.0	50.6	0.1	33.8	84.8
P1 High	208.4	11.1	203.8	200.6	2.2	3.7	12.6	9.7	3.0	14.9	35.6	4.7	61.4	80.4
P2 Low	58.4	25.0	62.4	113.6	-6.8	-94.5	36.1	98.6	3.6	91.8	78.1	2.7	18.3	5.4
P2 High	161.9	8.5	145.4	151.1	10.2	6.7	15.9	13.2	41.2	25.8	41.3	45.3	17.5	28.8
Gut fill (kg)														
P1 Low	4.6	24.7	4.7	4.4	-2.2	6.5	24.5	18.4	0.4	11.3	60.7	2.2	38.9	86.4
P1 High	5.3	24.1	5.8	5.0	-9.4	5.7	25.5	13.7	13.7	21.6	61.7	17.3	24.6	61.0
P2 Low	5.5	15.8	4.9	7.2	10.9	-30.9	19.3	43.7	32.1	50.0	12.5	41.1	55.5	8.9
P2 High	5.4	13.4	6.6	6.8	-22.2	-25.9	25.9	36.9	73.1	49.1	4.9	40.8	22.0	10.1

[A] Root mean square prediction error

[B] Mean square prediction error

[C] Fleece-free empty body weight

Both models demonstrated relative accuracy in the predicted rates of lean gain for H feeding level treatments with mean bias and RMSPE lowest for these treatments. The greatest mean bias and RMSPE was observed for the L2 treatment with over 85% of the error attributed to overall bias for both models, whereas random error contributed to 55.3 and 79.1 % of the prediction error for L1 treatments by the Oddy et al. (2022) and CSIRO (2007) models, respectively (Table 20).

Fleece free empty body weight and LW gain was predicted most accurately for H1 lambs by both models. The prediction of FFEBW was underestimated by both models for the H2 treatment and both showed over 80% of the prediction error was attributed to overall bias. The largest prediction error in FFEBW and LW gain was by the CSIRO (2007) model for the L2 treatment and in both cases over 90% of the prediction error was attributed to overall bias whereas LW gain was accurately predicted by the Oddy et al. (2022) model for the L2 treatment (Table 20).

Gut fill was least accurately predicted in the second feeding period by both models with the CSIRO (2007) model demonstrating larger mean bias and RMSPE values. The largest mean bias and RMSPE for the mass of gut fill contents by the Oddy et al. (2022) model was for the H2 treatments with 73.1% of the error attributed to overall bias. For the CSIRO (2007) model, random error was attributed to 8.9 and 10.1% of the gut fill prediction error for L2 and H2 treatments respectively (Table 20).

4.7.2 Prediction of carcass and viscera lean tissue gain by Oddy et al. (2022)

The prediction of NVEB lean tissue gain by the Oddy et al. (2022) model is shown in Table 21 and was least accurate for the L2 treatment with the largest mean bias and RMSPE observed and 91.1% of the prediction error attributed to overall bias (Table 21). Viscera lean gain was consistently underestimated with a larger mean bias and RMSPE observed for L1 and L2 treatments when observed and predicted values were close to zero. Most of the error for the prediction of viscera lean gain for all treatments was attributed to overall bias and slope bias (Table 21).

4.7.3 Overall prediction accuracy

The overall prediction accuracy of the models across all treatments is shown in Table 22. The CSIRO (2007) model estimated rate of fat gain was improved in comparison to the Oddy et al. (2022) model. A greater proportion of the prediction error for fat gain was attributed to random error for the CSIRO (2007) model compared to the Oddy et al. (2022) model (87.9 v. 37.8%; Table 22). The rate of NVEB lean tissue gain was overestimated by the Oddy et al. (2022) model with 67.4% attributed to random error. Viscera lean rate of gain was underestimated by the Oddy et al. (2022) model across all treatments with the error decomposition attributing 37.9% to random error and 59.3% to overall bias (Table 22).

The rate of lean tissue gain across all treatments were similar for the Oddy et al. (2022) and CSIRO (2007) models with 95.0 and 74.5% of the prediction error attributed to random error for both models (Table 22). The CSIRO (2007) model overestimated FFEBW and LW gain whereas the Oddy et al. (2022) model underestimated these parameters. For both models, the majority of the prediction error for FFEBW and LW was attributed to random error across all treatments. Gut fill was overestimated by both models but to a greater extent by the CSIRO (2007) model and 66.2% of the error was attributed to random error for the Oddy et al. (2022) model compared to 33.6% for the CSIRO (2007) approach (Table 22).

Table 21: Observed and predicted mean rates of fat-free non-viscera empty body (NVEB) gain and viscera lean gain with mean bias, RMSPE[A] and error decomposition. Observed values calculated by CT scans and simulated values from the model described by Oddy et al. (2022).

	Observed mean	CV of observations	Predicted mean	Mean bias (% obs mean)	RMSPE (% obs mean)	Error decomposition (% MSPE)		
						Overall bias	Slope bias	Random error
NVEB[c] lean gain (g/day)								
P1 Low	63.9	22.7	60.7	5.0	20.2	6.0	0.02	94.0
P1 High	94.3	17.4	100.4	-6.5	13.6	22.9	12.6	64.5
P2 Low	28.2	25.6	57.4	-103.5	108.4	91.1	4.0	4.9
P2 High	64.2	14.9	74.6	-16.2	22.1	53.4	14.5	32.1
Viscera lean gain (g/day)								
P1 Low	-19.2	-23.8	-26.3	-37.0	-41.3	79.1	17.8	3.1
P1 High	3.0	189.7	-5.3	280	346.3	63.2	12.8	24.0
P2 Low	-11.3	-35.1	-13.6	-21.2	-43.0	23.8	33.9	42.3
P2 High	1.9	294.5	-5.3	373.7	427.1	78.4	7.3	14.3

[A] Root mean square prediction error

[B] Mean square prediction error

[C] Fat-free non-viscera empty body

Table 22: Comparison of differences between observed values for all treatments overall calculated by CT scans and outputs from models described by CSIRO (2007) and Oddy et al. (2022).

	Observed mean	CV of observations	Predicted mean		Mean bias (% obs mean)		RMSPE (% obs mean)		Error decomposition (% MSPE)					
									Overall bias		Slope bias		Random error	
			Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO	Oddy	CSIRO
Fat gain (g/day)	65.6	41.4	49.0	63.1	25.3	3.8	33.4	21.2	57.3	3.3	7.9	8.8	34.8	87.9
NVEB[A] lean gain (g/day)	62.6	42.4	73.3	-	-16.9	-	30.6	-	30.8	-	1.8	-	67.4	-
Viscera lean gain (g/day)	-6.4	-165.6	-12.6	-	-96.9	-	-126.7	-	59.3	-	2.9	-	37.9	-
Lean gain (g/day)	56.3	58.3	60.7	60.7	-7.8	-7.8	35.2	34.0	5.0	5.4	0.0	20.1	95.0	74.5
FFEBW[B] gain (g/day)	121.9	43.6	109.7	123.8	10.0	-1.6	20.7	21.7	23.4	0.5	4.4	16.3	72.2	83.1
Liveweight gain (g/day)	129.6	48.2	122.3	140.4	5.6	-8.4	20.2	25.9	7.8	10.5	5.2	16.2	87.0	73.3
Gut fill (kg)	5.2	19.9	5.5	5.8	-5.8	-11.5	23.9	31.9	5.6	13.9	28.2	52.6	66.2	33.6

[A] Fat-free non-visceral empty body

[B] Fleece-free empty body weight

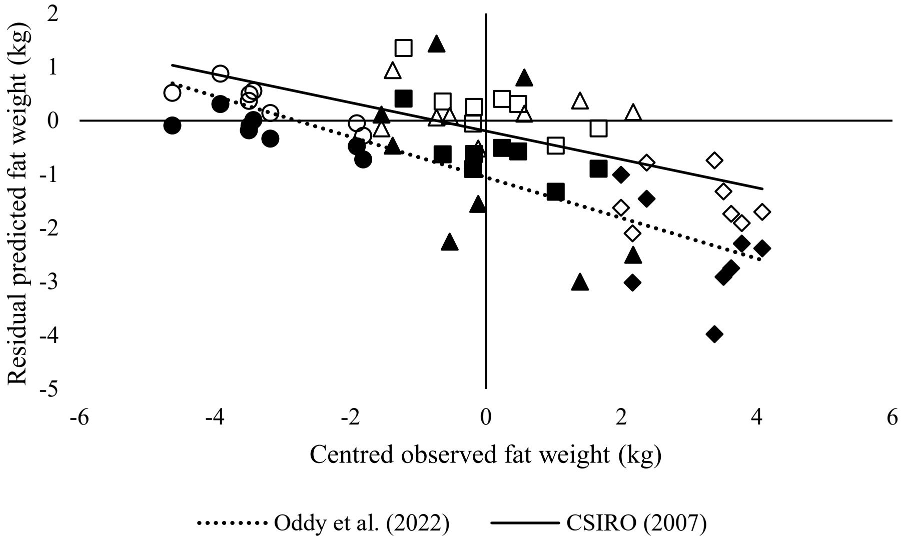


Figure 20: Observed fat weight values centred around the mean calculated using CT scans and the residuals of predicted values calculated by feeding systems described by CSIRO (2007; hollow symbols) and Oddy et al. (2022; solid symbols) at the conclusion of both feeding periods. Symbol shapes illustrate low (●) and high (■) feeding level in period one and low (▲) and high (♦) feeding level in period two.

The extent of underestimation of fat weight predicted values by both models for the high feeding level treatments in period two is illustrated by Figure 20 with fat weight underestimated to a greater extent by Oddy et al. (2022). The similar trendlines between simulated and observed lean weight values across feeding levels and periods irrespective of model is demonstrated by Figure 21.

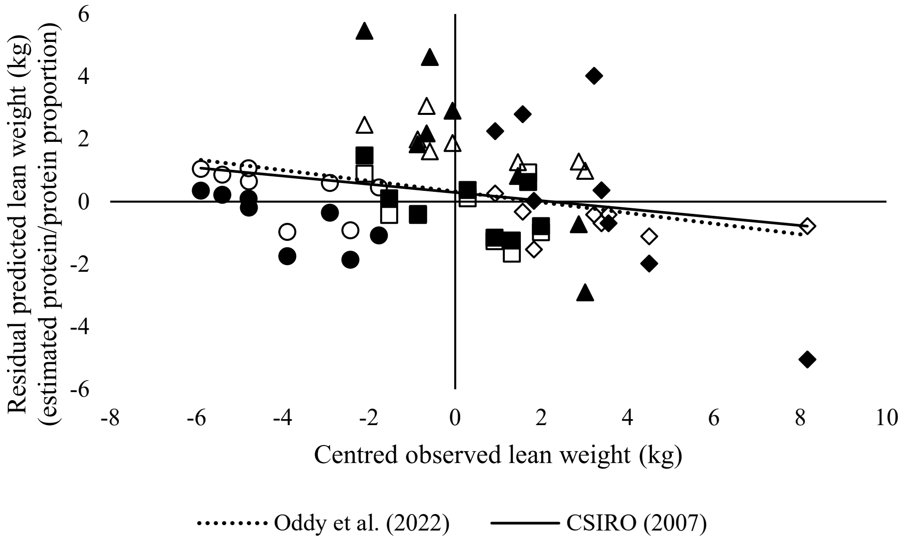


Figure 21: Observed lean weight values centred around the mean calculated using CT scans and predicted values calculated by feeding systems described by CSIRO (2007; hollow symbols) and Oddy et al. (2022; solid symbols) at the conclusion of both feeding periods. Symbol shapes illustrate low (●) and high (■) feeding level in period one and low (▲) and high (♦) feeding level in period two.

The predicted values for NVEB weight are similar to observed values albeit consistently overestimated (Figure 22), whereas viscera lean weight predicted values are underestimated and to a greater extent in the second feeding period (Figure 23).

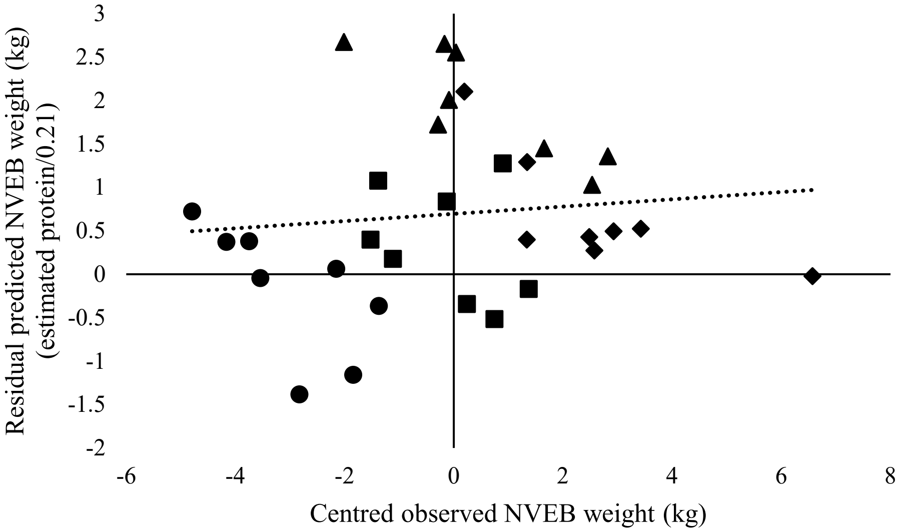


Figure 22: Observed fat-free non-viscera empty body (NVEB) weight values centred around the mean calculated using CT scans and predicted values calculated by the feeding system described by Oddy et al. (2022) at the conclusion of both feeding periods. Symbol shapes illustrate low (●) and high (■) feeding level in period one and low (▲) and high (♦) feeding level in period two.

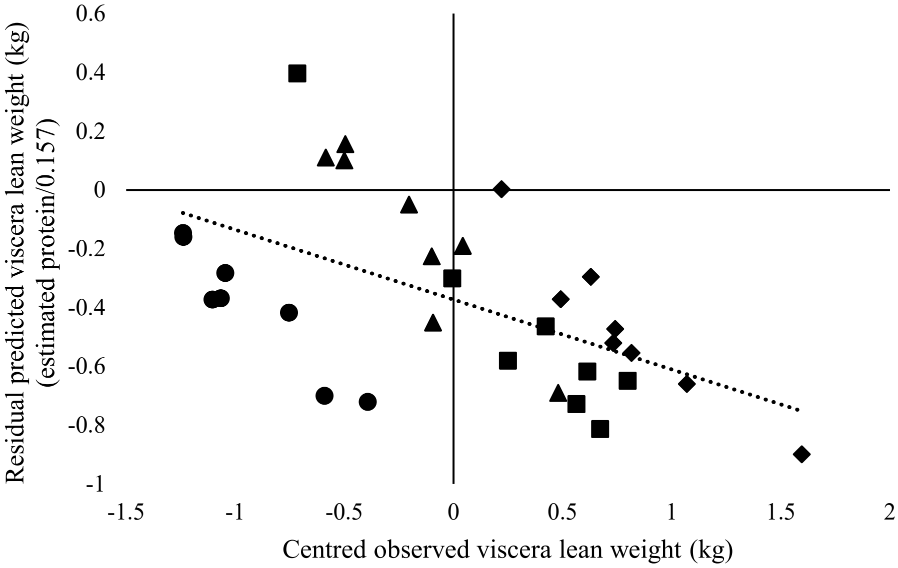


Figure 23: Observed viscera lean weight values centred around the mean calculated using CT scans and predicted values calculated by the feeding system described by Oddy et al. (2022) at the conclusion of both feeding periods. Symbol shapes illustrate low (●) and high (■) feeding level in period one and low (▲) and high (♦) feeding level in period two.

5. Discussion

5.1 Introduction

Intensively feeding lambs high-quality nutrients has the potential to exploit superior genetics and maximise lamb growth (Hegarty et al. 2006) increasing the per unit production of livestock systems whilst additionally mitigating emissions intensity (Davies et al. 2009; Alcock and Hegarty 2011; Harrison et al. 2014). It is estimated that in Australia between four and six million lambs sold for slaughter (20 to 30% of all lambs sold for slaughter) spend at least 35 days with grain as their primary food source (Meat and Livestock Australia 2020). Despite this, the survey of producers that own or operate a lamb feedlot reported that feeding systems, ration design, lamb growth rates and feed conversion ratios are highly variable. This indicated that there is no agreement amongst producers on best feeding practices.

The mean growth rates of 293 g/day (Figure 10) and mean feed conversion ratio of 5:1 (kg feed intake: kg liveweight gain; Table 7) reported by producers suggests that nutrient intake is the predominant constraint on lamb growth in lamb feedlots. This is because, to achieve these results with the described lambs, it would be necessary that the feedlot ration provided 12.5 MJ ME/kg DM using the current Australian feeding standards (CSIRO 2007). Cereal grains are capable of providing this amount of metabolisable energy to ruminants; however, they would need to contribute to a high proportion of total dry matter intake which increases the risk of acidosis if animals are not appropriately inducted to the feed source. The reported weight gains and FCR can therefore be considered achievable, and any expectations of lamb production above the levels reported here are unlikely without increasing nutrient intake.

The survey of lamb feedlot operators identified further constraints in lamb feedlots such as the incidence of acidosis (Figure 11) and shy feeding. A mortality rate of 1% was reported with nearly half attributed to acidosis. This means that somewhere between 20 000 and 30 000 lambs are dying from a preventable cause at a significant cost to producers. Furthermore, a median 3.5% of lambs that entered Australian lamb feedlots (more than 140 000 lambs) were identified as shy feeders and were removed from the feeding environment. The producer survey highlighted that the prevalence of shy feeders and acidosis are the most notable sources of production loss.

Another clear limitation to the production efficiency of the lamb feedlotting industry is the incidence of low lamb growth rates, with 16% of producers reporting lamb growth rates that were less than 200 g/day. This explains why the most common response to the open-ended question regarding knowledge gaps in the lamb feedlotting industry was that producers would benefit from the improved ability to predict growth rates and feed conversion ratios. The results of Experiment 1 further emphasised this with low growth rates observed in the feedlot, ranging from 79 to 148 g/day (Table 9).

To better understand these results an investigation of energy transactions in intensive feeding systems using CT scans of live lambs for repeat measures of body composition (Experiment 2) was conducted. These results were then used to inform and test a lamb growth model (Oddy et al. 2022) that better represents the realities of energy transactions in growing lambs in comparison to the current Australian feeding system model (CSIRO 2007). The broader use of the Oddy et al. (2022) model for research requires the evaluation of the CT scanning methods that inform it; however, the model showed good agreement with observed data as observed and predicted values from both models were not significantly different (Tables 20, 21 and 22). Further research and improvements to lamb growth models will result in the effects of nutrition on lamb growth becoming more predictable which will enable increased lamb feedlotting productivity.

This research demonstrated the inherent error in using liveweight alone to determine treatment effects in animal growth experiments. This is relevant when the experiment involves changes in diet composition and feeding level or when there are short intervals between liveweight measurements. These results provide valuable insight for researchers designing ruminant feeding experiments and point towards developing a repeatable approach to examine treatment effects on lamb liveweight and body composition with greater precision. Additionally, it demonstrates that changes in liveweight should be analysed over extended periods because of the effects of nutrient intake on gut fill which supports the findings of Robinson and Oddy (2001). Liveweight measurements are prone to errors and whilst liveweight measurements can be taken more frequently, it is not until available data encompasses approximately 70 days that growth rates can be reliably calculated.

The analysis of body compositional changes in animals fed differing feeding levels at two stages of maturity (Experiment 2) identified that there was no improvement in feed conversion ratio due to a prior nutritional restriction. This result leads to questions about what is frequently reported as compensatory gain. This experiment clearly highlighted the substantial change that occurs in the size of visceral organs following a dietary change which showcases why variations in liveweight gain are commonplace in commercial settings.

This research provides a unique and original contribution to the understanding of the effects of nutrition on lamb liveweight gain and body composition. The effects of nutrition on gut fill, organ mass and heat production energy costs have been outlined which will enable producers to have an improved understanding of the growth rates and feed conversion ratios they observe in intensive feeding systems. These results will contribute to the fine-tuning of a lamb growth model (P.PSH.0998) that will enable producers to better anticipate the costs, and calculate indicative returns, prior to the commencement of feeding and to more consistently and precisely meet market specifications.

5.2 Producer survey

The presence of shy feeders, the incidence of acidosis and the provision of low-quality fibre sources are reducing potential nutrient intake in lamb feedlots. An opportunity to increase energy intake will come from an improvement in the process of adapting lambs to a high-concentrate diet to increase feed intake and reduce social issues. There is an inherent difficulty in controlling individual animal intake whilst inducting lambs to high-concentrate diets in large groups (Bowman and Sowell 1997). Overconsumption of feed during this period can cause acidosis resulting in a reduction in rumen pH which causes feed aversion and decreased intake (Brown et al. 2000). Acidosis may be causing lambs to be conditioned to avoid a feed source (Burritt and Provenza 1997) which could implicate acidosis as a cause of shy feeders. Other potential explanations for the existence of shy feeders include bullying by dominant animals (Bowman and Sowell 1997) or other health issues that influence nutrient intake. Shy feeding is not associated with individual animal characteristics such as liveweight or temperament (Rice et al. 2016) which was supported by the survey result that 58% of producers returned lambs previously identified as shy feeders to the feedlot. Further investigation is required to identify the causes of shy feeders to mitigate these effects and it is recommended that changes in rumen pH during the induction period is analysed.

Low-energy density fibre was most frequently provided by the producers surveyed and is widely used in concentrate-based diets for ruminants (Galvani et al. 2014). Including a poor-quality feed source in the ration decreases the energy density of total feed intake (Kirby and Beretta 2004) and slows digesta passage rate which restricts dry matter intake (Dixon and Stockdale 1999). The provision of high-quality hay not only increased the energy density of the diet but also increased feed intake for lambs in a feedlot (File 1976). Dry matter intake could be increased through the processing of forages with the effects likely being greater for low-quality roughages than for high quality legume hays (Campling and Freer 1966; Wainman et al. 1972). The effects of the provision of lowly digestible forages on feed intake, diet digestibility and lamb growth rates requires evaluation with comparisons made to feeding high-quality and processed forages.

5.3 Experiment 1: Optimising preparation and adaptation of lambs to increase feed intake and subsequently growth rate

It was hypothesised that introducing lambs to a feedlot ration prior to feedlot entry would promote feed intake and increase lamb growth rates; however, low intake of supplements pre-weaning and low growth rates of lambs in the feedlot are likely explanations for why this was not observed in Experiment 1. The investigation provided some evidence that introducing lambs to a high-concentrate ration prior to feedlot entry increased intake and growth rates in the feedlot; although, the differences were not significant. Previous researchers have identified that adapting cattle to a high-concentrate diet over 34 days in comparison to 8 days reduced daily fluctuations in ruminal pH (Schwaiger et al. 2013a,b) and feed intake is increased by reducing these fluctuations (Brown et al. 2000; CSIRO 2007). Most producers in the survey introduced lambs to grain prior to entering the feedlot, which may help explain a median induction period of 10 days, shorter than current recommendations of 14 days (Dickson and Jolly 2011; Duddy et al. 2016).

The results of Experiment 1 demonstrated that supplementing pasture with grain via self-feeders may be one approach to extend the length of the adaptation period for lambs. Providing grain to lambs in the pre-weaning phase using creep feeding did not improve pre-weaning growth rates, likely due to the feed on offer in the paddock being of high quality and quantity (Figure 24; Oddy and Walmsley 2013). This provided high quality nutrients to the lambs from pasture intake and likely allowed ewes to maintain higher levels of milk production for an extended period (Gibb and Treacher 1978). The lambs grazing pasture grew rapidly from marking to weaning demonstrating minimal constraints on growth and metabolisable energy intake during this period (Oddy and Walmsley 2013). Pre-weaning supplementation had no effect on lamb growth rates likely due to substitution of grain and hay for pasture (Dixon and Stockdale 1999). The current research indicates that with high availability of quality pasture, competition with ewes pre-weaning is unlikely to impact lamb intake and growth rates.

Lamb growth rates declined on pasture post-weaning indicating that either nutrient quality or nutrient intake had correspondingly been reduced (Figure 24). It may be that lambs were slow to consume sufficient energy for gain due to the stress of weaning or high energy requirements throughout the weaning process associated with changes that occur in the stomach and organs. The effects of pre-weaning treatments on post-weaning liveweight and average daily gain (Figure 13) are difficult to explain and are more likely consequences of changes in stomach contents mass as demonstrated by empty body weight not being different between post-weaning treatments at feedlot entry despite differing entry dates. This suggests that immediately post-weaning there was no gain in lean or fat and the increase in liveweight observed by pasture treatments can be entirely attributed to a substantial increase in gut fill.

Figure 24: Photos of pasture availability pre-weaning (left image) and post-weaning (right image).

The growth rates of lambs in the feedlot were lower than expected for the high level of intake observed (Table 12). Explanations could include consequences of high feed intake such as greater than expected maintenance requirements (Ortigues and Durand 1995) and decreased diet digestibility (Graham 1980; Graham and Searle 1982), or animal health issues such as ruminal acidosis, gastrointestinal nematodes, and pneumonia (of which two deaths were attributed to). It is not possible to determine the reason or combination of reasons from the available data.

The predicted rates of fat and lean gain for lambs in Experiment 1 (based on CSIRO 2007) were similar and a moderate overall rate of gain was predicted (Table 12). The observed growth rate was much lower than predicted. The expected outcome of this was that there would be a decrease in fat gain relative to lean (Hegarty et al. 1999); however, fat gain was observed to be double that of lean. This finding may partially explain why growth rates were less than expected as the energetic requirement of lean gain per unit is less than that of fat (Oddy and Sainz 2002).

Increased fat deposition in the empty body of steers fed a high concentrate diet was attributed to their reduced visceral organ mass in comparison to forage fed steers (Oddy et al. 1997). Decreased visceral organ mass reduces maintenance energy requirements (Ortigues and Durand 1995), thus increasing energy availability for increased fat gain. In the current study, intake in the feedlot was not restricted and high levels of intake of both grain and straw were observed. This resulted in a large mean rumen volume at the conclusion of the experiment and would have also likely resulted in large visceral organ mass (Dougherty et al. 2022). Decreased maintenance requirements are therefore unlikely to be responsible for the greater than expected rates of fat gain in Experiment 1. It may be that the reduction in activity energy demand by the confinement of lambs allowed increased energy availability (Herd et al. 2004) but research on this topic is constrained by inherent difficulties in quantifying these effects.

5.4 Learnings about how to better measure treatment effects in experiments

The use of CT scans clearly demonstrated that changes in liveweight are not always reflective of body compositional changes as it is often assumed. At the end of a feedlot finishing period in the nutritional management experiment, mean lamb liveweight was 43 kg with the contribution of the estimated weight of stomach contents ranging from 13 to 27% of that weight. Due to the observed high levels of intake of both a mixed grain ration and straw, mean stomach volume increased from 4.4 L at weaning (35 kg liveweight) to 8.0 L at the end of the finishing period. The mean increase in liveweight for the lambs weaned directly into the feedlot to the end of the experiment was 8.1 kg and of that, it is estimated, that 44% of this increase (3.6 kg) was due to the increased weight of stomach contents.

Additionally, over 70% of the change in liveweight of lambs weaned onto pasture for the 30 days between weaning and feedlot entry was attributed to the increased weight of stomach contents. This resulted in no difference in empty body composition between lambs that entered the feedlot at weaning and those that were initially weaned onto pasture and entered the feedlot 30 days later. These results indicate that factors including stomach contents, can affect the accuracy of liveweight as the sole predictor of animal performance, particularly with changing diets and short intervals between liveweight measurements.

These findings suggest that the analysis of energy intake could be a more reliable indicator of empty body tissue gain. Utilising energy intake measurements in confinement feeding systems to determine productive performance would rely on the precise prediction of the effects of nutrition on empty body gain and feed conversion. It was demonstrated using CT scans in the nutritional management experiment that empty body gain was only 73 g/day and for the level of nutrient intake observed it was expected to be 207 g/day using the current Australian feeding standards (CSIRO 2007; Table 12). This suggests the capacity of predictive lamb growth modelling to inform commercial producers that are intensively feeding lambs of empty body gain is not yet reliable enough.

5.5 Experiment 2: Level of feeding and stage of maturity affects diet digestibility and protein and fat deposition in cross-bred lambs

Compensatory growth

Lambs were fed a high or low feeding level at two stages of maturity and half of the lambs were swapped between treatments for the later feeding period following a ten week pasture grazing period between the feeding periods. It was identified that lambs fed a restricted feeding level in the first feeding period were not able to catch up or compensate for the prior nutritional restriction when increased nutrients were provided in the second feeding period. This demonstrated an absence of compensatory gain as the prior nutritional restriction did not improve the efficiency of tissue gain which has previously been alluded to by Hegarty et al. (1999) amongst others. Hegarty et al. (1999) identified an improved feed conversion ratio at equal energy intakes for previously restricted lambs and slaughter data confirmed this result was due to an increase in the rate of carcass protein gain. It was noted that lambs from differing nutritional histories had different visceral organ masses at the commencement and conclusion of feeding (Hegarty et al. 1999) whereas there were no differences in viscera lean mass irrespective of nutritional history in the current research. The data from this research supports an alternative explanation for the results observed by Hegarty et al. (1999) in that there is a lag in the change of visceral organ mass and therefore heat production energy losses following a dietary change.

There was no interaction between feeding periods for lamb growth or feed conversion ratio and lambs from the low feeding level in period one remained lighter by the same extent at the start and conclusion of the second feeding period. The difference between the current experiment and that of many others that have provided evidence for compensatory growth is that irrespective of P1 treatment, lambs in the current research commenced the second feeding period following 10 weeks grazing dried naturalised pasture. This was enough time to allow the visceral organs to adjust to the diet irrespective of previous feeding level as visceral mass of sheep achieves a steady state within approximately 6 weeks after a change in diet (Burrin et al. 1990).

Feeding level during period one had no effect on estimated stomach contents or viscera lean mass at the commencement of the feeding period two. This would have resulted in similar energy losses to heat production (Graham et al. 1974; Koong et al. 1985; Ortigues and Durand 1995). Visceral organs represent between six and 10% of empty body weight but they contribute at least 50% to whole-body cardiac output, protein synthesis and heat production for animals fed above maintenance levels (Burrin et al. 1990; Ortigues and Durand 1995). The lag time for changes in visceral organ mass and energy expenditure following a restriction in feed intake have been shown to vary between six and 21 days (Clapperton and Blaxter 1965; Wainman et al. 1972). Ortigues and Durand (1995) identified that the gastrointestinal tract responded to underfeeding within five days and the response of the liver took between five and ten days. The results of Experiment 2 demonstrate that when visceral organ mass and energy intake are equal and the lambs were at the same stage of maturity, compensatory growth does not occur irrespective of prior nutrition. What has previously been referred to as compensatory gain (Drew and Reid 1975; Turgeon et al. 1986; Sainz et al. 1995) may be primarily due to a change in feeding level for previously restricted animals rather than a change in the efficiency of energy utilisation for gain. It is recommended that this is investigated further with a greater nutritional restriction.

Diet digestibility

The digestibility of the diet did not differ between feeding levels in the first feeding period (71.5 ± 0.9%) but was reduced in the second feeding period at the higher feeding level (67.3 ± 0.4 v. 71.1 ± 0.4%; $P<0.001$). The residence time of digesta in the rumen and digestive tract is faster in lambs with higher intake, reducing DM digestibility (Graham and Searle 1982; Margan et al. 1982). The finding that calculated stomach volumes using CT scans were not vastly different at the end of both feeding periods might indicate that the effects of level of feeding on diet digestibility are more closely related to intake as a proportion of stomach capacity rather than animal maturity.

Efficiency of energy utilisation for empty body weight gain

When the energy available for gain is calculated from estimated maintenance requirements (CSIRO 2007), the efficiency of energy use for gain improved in older lambs and at higher levels of intake (Table 15). This is despite a reduction in the energy density of the diet at the higher feeding level in P2 (Table 3). These results are consistent with the findings of Graham (1980); however, the effects of changing levels of nutrition on viscera mass and consequent heat production energy costs (Koong et al. 1985; Ortigues and Durand 1995; Oddy et al. 1997) are not accounted for in current maintenance energy calculations. In addition, any reduction in lean tissue mass because of nutritional history would reduce the theoretical efficiency of energy use for gain; protein deposition was expected to make up a greater proportion of empty body gain for all treatments (CSIRO 2007; Table 15).

Fat deposition in the current study demonstrated a similar pattern to the data of Hegarty et al. (1999) which indicates that lambs subjected to a period of weight stasis have similar priorities for fat deposition as less mature lambs. The rate of fat gain in lambs is principally determined by stage of maturity and rate of empty body gain. It was expected that fat deposition as a proportion of retained energy would also demonstrate a similar pattern; however, lambs at lower levels of feeding deposited proportionately greater amounts of fat. The proportion of fat in retained energy is dependent on the changes in lean tissue mass, which means that if there is a restriction or reduction in the rate of lean tissue deposition, fat deposition increases proportionately.

Another potential explanation for fat deposition being proportionately greater at lower levels of feeding are that a reduction in viscera lean mass at lower levels of intake reduces maintenance energy requirements (Ortigues and Durand 1995) potentially resulting in more energy availability for gain and increased fat deposition (Oddy et al. 1997).

5.6 Experiment 3: The effects of diet composition and grazing on the rate of lean and fat deposition in composite lambs

Lambs were fed one of two rations in a feedlot with a third treatment grazing lucerne in a paddock in experiment 3. The feedlot rations included a barley based pelleted diet which incorporated lucerne chaff and without access to additional fibre (ration 1) or a barley based pelleted diet without lucerne chaff and the fibre component of the ration provided separately as lucerne hay fed in long form (ration 2). Due to lower-than-expected intake of lucerne hay for the ration 2 treatment, likely due to wet weather and spoilage, lambs fed ration 1 had increased daily dry matter and metabolisable intake (Table 18). This resulted in ration 1 having increased empty body gain in comparison to ration 2. Feed intake of pasture fed lambs was unknown and empty body gain was less than ration 1 and approximately equal to ration 2 (Table 17).

Lambs grazing lucerne had a lower stomach volume at the start and end of the experimental period demonstrating the rumens adaptation to diet composition. It was anticipated that the provision of hay would also increase stomach volume for the ration two treatment; however, intake of hay was low resulting in lower dry matter intake. The similar stomach volume between ration 1 and 2 is possibly explained by the similar NDF intake and a marginal difference in ADF intake between treatments (Table 18).

The rate of fat gain was increased for both rations fed in the feedlot in comparison to the lambs grazing in the paddock (Table 17). The increased lean gain observed for the pasture fed animals in comparison to ration 2 can be explained predominantly by the increase in viscera lean mass with changes attributed to diet composition and feed intake levels (Burrin et al. 1990; Dougherty et al. 2022). The lean gain was not different between ration 1 and pasture fed animals likely due to the increased energy intake and rate of empty body gain for ration 1 lambs.

It has been shown that rate of fat gain in the empty body responds to energy intake (experiment 2; Hegarty et al. 1999), and the results from Experiment 3 further supported this understanding (Figure 17). Therefore, the lower fat gain of lambs grazing lucerne pasture may be due to decreased energy availability for that treatment. Oddy et al. (1997) identified that the decreased rate of fat gain observed for forage fed steers in comparison to concentrate fed steers by Sainz et al. (1995) could be entirely attributed to the increased visceral organ mass and resultant greater energy expenditure for maintenance. An increased viscera lean mass could also explain the reduced energy availability for fat gain for pasture fed animals in the current experiment. Additionally, the animals at pasture have an additional energy expense of activity including walking, grazing and moving about which could be contributing. It was anticipated that providing roughage separately in the feedlot (ration 2) would stimulate viscera lean mass to be similar to pasture fed animals thus providing some indication of activity energy costs; however, low intake of hay in this treatment meant this was not able to be determined.

Despite differences in rate of fat gain between treatments, rate of gain in the NVEB was not different and was numerically greater for the pasture treatment compared to ration 2 (Table 17). Rate of gain of NVEB is similarly responsive to energy intake but is also determined by mature weight and stage of maturity; however, there was no difference at the commencement of this experiment in NVEB mass demonstrating that all treatments were at the same stage of maturity. It would therefore be expected that rate of gain in the NVEB would be decreased for the pasture treatment. It appears that either diet composition or the activity of grazing and walking may be stimulating NVEB empty body gain; however, results are not conclusive. The results presented in Figure 17 provide limited evidence that diet composition is stimulating NVEB rate of gain as it appears for the same energy intake, ration 2 treatment lambs have the same rate of fat gain but increased rates of NVEB gain. There were no differences between treatments likely due to the high variability observed between animals and limited numbers.

Further research is required to determine the contribution of activity energy to maintenance energy costs and to explain why lambs fed high forage diets and grazing pasture are typically leaner than their concentrate fed counterparts.

5.7 Modelling lamb growth

The current study supports the overall appropriateness of the CSIRO (2007) feeding system for the formulation of the nutrient requirements of lambs. The overall predicted rates of lean, fat, FFEBW and LW were similar demonstrating the overall high prediction accuracy of lamb growth and body composition. It was clear that this model is susceptible to some errors, especially at later stages of maturity and due to nutritional history. The model by CSIRO (2007) is limited by its inability to adapt to changing visceral lean mass following a change in feeding levels or diet composition. Additionally, the model uses a single term for the efficiency of energy utilisation for gain, irrespective of feeding level and stage of maturity, which has previously shown to be problematic (Graham 1980). The model by Oddy et al. (2022) was less accurate than CSIRO (2007) and a greater proportion of the prediction error was attributed to overall bias. This was particularly true for the predicted rates of fat gain. However, the model by Oddy et al. (2022) better represents the realities of energy transactions in the growing ruminant and with further refinement is likely to be an invaluable tool. The use of this model, in the current study, also highlighted specific areas for future investigation to advance our understanding of ruminant energy transactions and the responses to a changing feed supply.

The utilisation of metabolisable energy for empty body weight gain increased with stage of maturity (Table 15; Graham 1980). Additionally, higher levels of feeding resulted in an improvement in the efficiency of energy utilisation for empty body weight gain. The current Australian feeding standards (CSIRO 2007) calculates the efficiency of energy utilisation for empty body weight gain based upon the energy density of the diet irrespective of feeding level or stage of maturity. The efficiency of energy utilisation for empty body weight gain in the CSIRO (2007) model is a single term that incorporates both protein and fat gain. The changing composition of empty body gain with increasing energy intake and advancing stage of maturity (Graham 1980; Hegarty et al. 1999; Table 15) is not considered. The lower heat production of fat deposition is therefore not accounted for (Oddy and Sainz 2002) resulting in a perceived improvement in energy utilisation for empty body weight gain when proportionately more fat is being deposited. When the CT scan-derived observed values for body compositional changes in the current research were compared to predictions of the CSIRO (2007) model, fat gain was underestimated for the high feeding level in the second feeding period (Table 20). This result may be explained in part by the absence of an adjustment to the calculated efficiency of energy utilisation for empty body weight gain at later stages of maturity and at high levels of energy intake.

The energy available for empty body weight gain is calculated by subtracting estimated maintenance energy requirements from metabolisable energy intake (CSIRO 2007). Maintenance energy requirements are variable and the partitioning of energy costs into maintenance and growth-related processes is not truly feasible, resulting in confounded estimates of maintenance energy requirements and the energetic efficiencies of protein and fat deposition (Knap 2000). The energy consumption of lean tissues varies considerably due to differing rates of protein turnover and muscle proteins generally have lower rates of turnover than most organs (Oddy et al. 2019). Additionally, the energy used by organs has been shown to be the product of organ size and their metabolic activity per unit of tissue as changes in organ size alone can account for observed differences in whole body metabolism (Burrin et al. 1990; Oddy et al. 1997).

The growth model outlined by Oddy et al. (2022) likely better represents the realities of energy transactions in growing ruminants as it separates the energy costs of lean tissue mass and gain into carcass and viscera depots. It is not reliant on calculated maintenance energy requirements or a single term for the efficiency of energy utilisation for empty body weight gain but instead relies on the accurate prediction of heat production from predicted empty body composition and rate of tissue gain. Despite this, when predictions by the Oddy et al. (2022) model were compared to CT scan-derived observed values, fat gain for the high feeding level in feeding period two was underestimated (Table 20). The overestimation of fat-free non-viscera empty body lean gain in the same lambs indicates that either the model is incorrectly partitioning retained energy to fat and lean gain or the partitioning of lean and fat tissue using CT scans is erroneous. The inability to manually remove intestinal contents from CT scan images may also partially explain the underestimated fat gain. This is because the inclusion of intestinal contents may result in an overestimation of viscera lean mass and consequently heat production energy costs by the model, reducing the predicted rate of fat gain for every unit of energy intake. Further verification of the CT scans using comparative slaughter is recommended in addition to further evaluation of the model parameters for estimated heat production energy costs and the partitioning of retained energy to tissue gain.

5.8 The capability of CT scanning to advance ruminant feeding systems and predictive growth modelling

The current research demonstrated that CT scans can inform predictive growth models of body compositional changes in individual animals. To get the same amount of data as reported by this research, a comparative slaughter study would require four times the animals and a similar increase in laboratory work for analysis. CT scans allow changes in body composition to be assessed with a minimal number of animals, reducing costs and labour, and additionally enabling longer feeding experiments that can include more frequent analysis of the rate of empty body tissue gain.

Previous researchers have demonstrated high levels of accuracy between CT derived estimates of carcass composition and the dissection of slaughtered lambs (Sehested 1984; Vangen and Jopson 1996; Macfarlane et al. 2006; Haynes et al. 2010). Gunderson and Jensen (1987) that by using at least 10-15 CT scans of the empty body, the volume and subsequently the weight of any body component can be predicted with 95% accuracy. The results in experiment 3 highlight the accuracy of the prediction of carcass weight and body composition when compared to carcass weight via slaughter and DEXA scans of body composition. The estimation of carcass weight required estimations of the weight of stomach contents, skin weight and the weight of the head and feet which may have contributed to the variation observed (Figure 18). The relationship between the volume and weight of stomach contents estimated by CT scanning is almost identical to that of De

Barbieri et al. (2015) (Figure 6) when it was also identified that post-mortem weights and those estimated using CT scans were highly correlated (r^2=0.92).

For broader application of CT scan data it would be beneficial to develop a method to accurately account for intestinal contents which are unable to be manually removed from CT scan images. The evaluation of CT scan estimates of stomach contents and visceral lean mass with lambs fed a variety of diets and feeding levels would likely enable CT scans to more accurately inform predictive growth models, and could facilitate the prediction of feed intake in grazing sheep and lambs. This would allow more accurate experimentation in grazing animals and could facilitate much simpler and larger scale data collection.

This research demonstrated that repeated measures of individual animal body composition can be utilised in analyses of responses to feed supply. Oddy (1999) stated that if these tools were developed, it may be possible to detect variation in the partial efficiency of protein gain, resulting in the ability to select animals for their efficiency of nutrient use. It is recommended that in addition to measuring individual animal intake, that future research utilises diverse genotypes to explore genetic variation in partial efficiency of nutrient use for protein gain. If it can be demonstrated that genetic variation in partial efficiency exists, then it may be possible to select for this.

6. Conclusion

6.1 Key findings

- Nutrient intake is the predominant constraint to maximising lamb growth rates in intensive feeding production systems and improving adaptation to diet and diet composition are key components to improving production.
  - There is evidence that increased nutrient intake could be facilitated by improvements in the management of the adaptation period, particularly by increasing the length of time lambs are exposed to the diet prior to feedlot entry. Further research is necessary to confirm this.
  - Diet composition including the chopping, grinding of forages, and using high-quality forages as a fibre source could increase nutrient intake whilst decreasing heat production energy losses by reducing the size of the gastrointestinal tract.
- There is potential that providing lambs with a feedlot ration prior to feedlot entry could increase feed intake and growth rates in the feedlot but more research is required.
  - Lamb growth rates pre-weaning are not improved by the provision of additional supplements pre-weaning with a high quantity of high-quality feed on offer.
  - The use of liveweight particularly over short periods and with changing diets is problematic for the accurate interpretation of results.
- The commonly reported phenomenon of compensatory growth was not observed in the current research highlighting the importance of accurately predicting heat production energy costs to better predict growth responses.
  - Rate of fat gain is determined by the availability of energy for gain and lambs at later stages of maturity deposit proportionately more fat than less mature lambs.
  - The efficiency of energy utilisation for gain increased with increasing feeding level and advancing stage of maturity; however, it is more likely these results can be explained by

    the increased proportion of fat in the empty body gain and the inability to accurately specify maintenance energy requirements.
  - The use of a single term for the efficiency of energy utilisation for gain does not represent the realities of energy transactions in growing ruminants and is especially problematic with high rates of fat gain at high feeding levels and later stages of maturity.
- Lambs fed high concentrate diets and in confinement deposit a greater amount of fat and decreased lean tissue in comparison to pasture fed animals.
  - An improved understanding of the effects of nutrition and activity on body composition and liveweight gain is necessary
- CT scanning of lambs demonstrated advantages for research purposes, in comparison to comparative slaughter studies, due to it being a non-destructive method for repeated measures of body compositional changes in growing lambs. Repeated measures on individual animals using CT scanning may allow identification of between-animal variation in efficiency of tissue deposition for genetic selection and comparison of diverse genotypes (e.g. Merino, cross-bred and shedding sheep).

6.2 Benefits to industry

The intensive feeding of lambs to accelerate lamb growth, particularly from weaning to slaughter, has the greatest potential to increase production and reduce emissions intensity. The feedlot finishing of lambs provides an opportunity to overcome the seasonal limitations of feed supply that commonly exist in extensive pasture-based systems and is capable of consistently providing high-quality nutrients to lambs without any restrictions on intake. The cost of feed in these systems in comparison to extensive pasture-based systems is a substantial limitation to profitability. The ability to accurately predict a growth response, especially of carcass components, to available nutrients would therefore be of benefit to producers as they would be able to anticipate the costs of intensively feeding prior to the commencement of this practice and provide indicative returns.

This research outlines potential explanations for the variability in lamb growth rates commonly observed in both commercial and research situations. The greater understanding of the effects of nutrient supply on gut fill, organ mass and body composition will enable commercial producers and other professionals in the red meat industry to better understand the observed growth responses of ruminants to feeding in commercial intensive feeding operations. It provides a methodology for researchers to conduct experiments to determine treatment effects with greater precision and will hopefully stimulate researchers to not rely solely on animal liveweight to make conclusions. This research clearly identifies opportunities for further research to improve the precision of predictive growth modelling, improvements in which will have a substantial impact on the red meat industry.

7. Future research and recommendations

The current research was limited by:

- Online survey methodology – this limited participation to respondents regularly using social media and there was no way to ensure responses were accurate representations of their feedlot operations.
- Seasonal conditions – the high quantity and quality of pasture available to lambs and ewes prior to weaning in experiment 1 resulted in low supplement intake and insignificant

treatment effects. Rapid lamb growth rates were observed likely due to the high milk production of ewes and little, if any, competition for pasture.
- Intake measured on a pen/plot basis – this limited the analysis of the effects of prior nutrition on intake in the feedlot, and also the assessment of between animal variation in body compositional changes.
- CT scan accuracy – the evaluation of CT scan derived estimates of body composition requires verification, in particular the weight of the visceral organs and stomach contents.
- Limited genotypes and feed types tested – to evaluate the precision of any model it must be tested across a variety of characteristic circumstances.

Future research opportunities/considerations:

- A longitudinal study collecting data from diverse feedlots, preferably covering multiple seasons. This will likely facilitate the concurrent investigation into the causes and prevalence of shy feeders and acidosis as occurrences will be more numerous in commercial settings. The inclusion of ruminal pH monitoring during adaptation periods should be considered to examine relationships between rumen pH, shy feeding and feed intake.
    - To calculate the cost of shy feeders it would be necessary to collect data regarding management of shy feeders (i.e. the proportion that die, are sold immediately, are moved to pasture and eventually sold and the proportion that are later returned to the feedlot). Information on the cost of lamb purchases would also be necessary.
- Assessment of benefits of creep feeding and backgrounding across multiple seasons (to capture conditions of lower fed quality and availability) and/or using twin-born lambs.
- Research to better understand the effects of pasture characteristics on supplement intake at pasture
- Research that includes recording of individual animal grain intake both at pasture and in the feedlot, and roughage consumption in the feedlot, is recommended to develop precise feed intake targets for the development of best practice nutritional management guidelines prior to entering a feedlot.
- Experiments feeding a wide range of diets and feeding levels to lambs in confinement feeding to further evaluate and develop predictive lamb growth models.
- Recommended that individual animal intake and the analysis of diet digestibility are incorporated for more conclusive results. This could be extended to exploring body composition changes in different genotypes to investigate between animal variation in the efficiency of protein deposition.
- Further investigation into the potential lag in changes in visceral organ mass and resultant heat production energy costs following a dietary change to explain previous reports of improved feed conversion ratios following a dietary restriction.

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9. Appendix

9.1 Literature Review

9.1.1 Introduction

The demand for animal agriculture is expected to increase rapidly (Rae and Nayga 2010) and meeting the emerging market opportunities will require innovative and practical adaptation strategies. Animal agriculture faces challenges such as greater competition for rural land resources, increasing input costs and the increased scrutiny of the contribution of livestock to climate change (Henry et al. 2012). Intensively feeding lambs to accelerate lamb growth from weaning to slaughter has greater potential to increase the per unit production of livestock systems and simultaneously mitigate emissions intensity compared to genetic selection (Hegarty et al. 2006; Alcock and Hegarty 2011). The improved understanding of the factors that affect the efficiency of nutrient use is necessary to intensify production in a sustainable and cost-effective way.

Growth is an increase in size due to the accretion of lean tissue (protein), fat and bone and includes both structural and functional development. Growth is regulated by the animal’s genetic potential and the extent to which environmental constraints allow this to be expressed, of which nutrition is considered the most influential (Oddy and Sainz 2002; Hegarty et al. 2006). A lamb’s genetic growth potential is determined by its mature size, which is an appropriate reference point to describe the pattern of growth (Butterfield 1988). Between genotypes, the pattern of deposition of tissues is similar when scaled to mature size (Butterfield 1988). The relative proportion of protein and fat in the body changes in favour of fat deposition as an animal advances in maturity and, at any given liveweight, an animal with a greater mature weight will be less mature and leaner than one with a smaller mature weight.

Whilst conceptually the unrestricted growth of a lamb and thus the realisation of its’ genetic potential is relatively simple to comprehend, the reality is that in commercial settings, it is unlikely to be frequently observed (Oddy and Walmsley 2013). This review will therefore explore the potential constraints on lamb growth rates in commercial settings that are likely inhibiting the realisation of genetic potential. It aims to identify opportunities for further research with a particular focus on intensive feeding systems such as lamb feedlots. It will:

a) outline current lamb growth rates available from the literature
b) investigate the management of the weaning transition period with a focus on the development of the rumen
c) explore potential constraints on nutrient intake
d) identify opportunities to increase nutrient intake and improve diet digestibility
e) investigate the effects of genetic selection
f) describe the impacts of nutrition on the composition of liveweight gain
g) outline the implications of the composition of liveweight gain on feed conversion

9.1.2 Current lamb growth rates and theoretical genetic potential

The unconstrained growth of a lamb with a maximum liveweight of 90 kg modelled using the Gompertz growth equations described by Johnson et al. (2012) is shown in Figures 1 and 2. These equations reveal that a lamb could potentially grow at a rate of 260 g/day from birth to six weeks of age and 370 g/day from six weeks to weaning (at 12 weeks). For the eight weeks post-weaning it was predicted that a lamb realising its genetic potential would grow at 380 g/day (Figures 1 and 2). These values will increase for breeds with heavier maximum weights and reduce for smaller breeds (CSIRO 2007; Johnson et al. 2012).

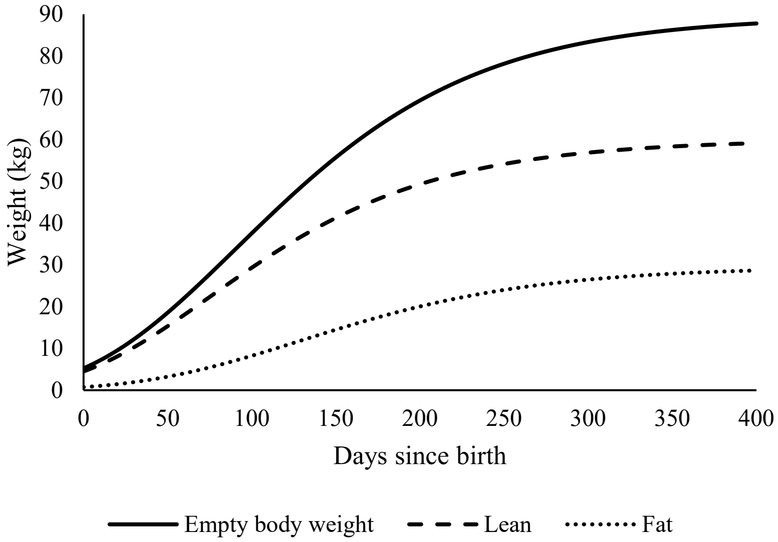

Figure 1. The empty body, lean and fat weight of a lamb demonstrating unconstrained growth with a maximum liveweight of 90 kg. Modelled using the approach described by Johnson et al. (2012).

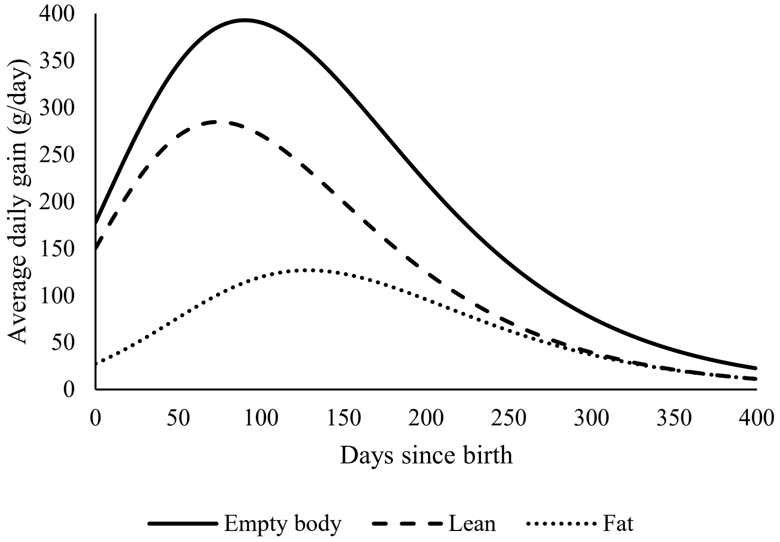

Figure 2. The rate of empty body, lean and fat average daily gain of a lamb demonstrating unconstrained growth with a maximum liveweight of 90 kg. Modelled using the approach described by Johnson et al. (2012).

The data available in the literature indicates that growth rates prior to weaning are usually greater than post-weaning (Table 1). Additionally, prior to weaning, lamb growth rates are similar to theoretical unconstrained growth; however, post-weaning, lamb growth rates are usually well below the expected potential (Table 1). This is also supported by the analysis of pre- and post-weaning lamb growth rate data from both the Sheep CRC Information Nucleus Flock and from Australian sheep seedstock enterprises including a variety of breeds (Oddy and Walmsley 2013).

Table 1. Comparison of pre- and post-weaning lamb growth rates reported in the literature. All lambs are progeny of terminal sires joined to cross-bred ewes.

Reference	Number of lambs	Pre-weaning (g/day)	Post-weaning (g/day)
Afolayan et al. 2007	11 341	239	147
Ali et al. 2005a,b	279	228	333^{A}, 244^{B}
Hall et al. 2001 (High^{A})	1 159	296	187
Hall et al. 2001 (Low^{B})	1 157	294	99
Hegarty et al. 2006 (High^{A})	193	294	121
Hegarty et al. 2006 (Low^{B})	193	198	81
Orr et al. 2019	589	290	164

^{A}Feedlot finished
^{B}Pasture for approx. 60 days before feedlot for approx. 80 days
^{C}High allocation of pasture (postweaning only - Hall et al. 2001)
^{D}Low allocation of pasture (postweaning only - Hall et al. 2001)

Pre- and post-weaning growth rates are dependent upon nutrition during these periods and there are occasions where growth rates post-weaning have been greater than pre-weaning (Ali et al. 2005a,b; see Table 1). Pre-weaning lamb growth rates are heavily reliant on ewe milk production particularly in the early stages of lactation when milk contributes to the majority of a lambs' nutrient intake (Langlands 1972; Morgan et al. 2007). Ewes are generally able to compensate for poor pasture availability for the first six weeks of lactation by mobilising fat tissue (Gibb and Treacher 1978). After the first six weeks of lactation, milk production is dependent on the condition of the ewe and the ewe's nutrient supply. The contribution of milk to a lambs' total energy intake after the first six weeks of lactation will therefore depend on these factors and will affect their growth rates (Morgan et al. 2007).

In an experiment that attempted to maximise pre-weaning lamb growth rates, Muir et al. (2003) joined ewes and sires with high breeding values for growth rate. With "extremely good feeding conditions", growth rates to 12 weeks of age averaged 409 g/day. The authors identified that there are very few reported growth rates pre-weaning greater than 300 g/day and their results demonstrate the gulf between what is achievable and the reality. It is possible that ewes and rams with high growth rate breeding values have greater mature weights than the lambs on commercial farms and the values used for the growth modelling in Figures 1 and 2. This may explain why the growth rates observed to weaning by Muir et al. (2003) were much higher than those reported in the literature (Table 1).

The contribution of fat tissue to empty body gain in young lambs is minimal (Butterfield 1988; Figure 3). The energy intake required for every unit of liveweight gain is reduced in young lambs due to the lower energy content of protein per unit mass, in comparison to fat, and the high-water content of lean tissue (Dougherty et al. 2020). Furthermore, maintenance energy requirements of young lambs are low because maintenance requirements are highly correlated with total empty body protein mass (Graham et al. 1974). This is particularly true for lambs extracting most of their energy supply from milk. Milk bypasses the rumen and is highly digestible resulting in a smaller gastrointestinal tract in comparison to a grass-fed ruminant (Warner et al. 1956) which further reduces heat production energy costs (Ortigues and Durand 1995). Whilst these factors are largely responsible for lamb growth rates pre-weaning typically being greater than post-weaning, there are exceptions. For example, when there is poor pre-weaning nutrient supply for ewes and lambs (Thompson et al. 2011) or due to the presence of a parasite burden and disease (Sykes 1994; CSIRO 2007).

The lambs in Table 1 were mostly reared on pasture post-weaning; however, lambs placed in a feedlot post-weaning by Ali et al. (2005a,b; Table 1) exhibited higher growth rates than pre-weaning. The confinement feeding of lambs on concentrate-based diets frequently facilitates faster growth rates in comparison to pasture fed animals (Table 2). This finding has been predominantly attributed to the ability to consistently supply feed of high energy density utilising a concentrate-based diet (Zervas et al. 1999). Lambs consuming a pasture-based diet commonly exhibit highly variable growth rates due to the constraints that seasonal variations in nutrient supply place on diet digestibility and feed intake (Moore et al. 2007). Feed intake at pasture can be constrained by low pasture availability or, with high pasture availability, by rumen capacity and the rate of passage of digesta. Slow passage of digesta is more pronounced with lower quality pasture (Margan et al. 1982). Feeding an energy dense (high concentrate) diet with no restrictions on availability would likely result in more consistent nutrient supply particularly over an extended period.

Table 2. Comparison of lambs of the same age and genotype within studies finished on either pasture or fed a concentrate diet in confinement.

Reference	Initial liveweight (kg)	Confinement (g/day)	Pasture (g/day)	Pasture type
Borton et al. 2005	24.0	330	120	Ryegrass
McClure et al. 1994	24.0	257	220	Lucerne
McClure et al. 1995	27.6	351	223	Lucerne
McClure et al. 2000	23.0	358	282	Lucerne
Murphy et al. 1994	28.0	325	191	Lucerne
Resconi et al. 2009	28.2	202	91	Birdsfoot Trefoil
Zervas et al. 1999	29.0	246	200	Improved pasture

Several studies have demonstrated that pasture fed animals can exhibit similar growth rates to concentrate fed lambs by grazing high quality pastures or through the supplementation of pastures with a grain supply (Velasco et al. 2004; Atti and Mahouachi 2009; De Brito et al. 2017). Reviews of the growth rates reported in the literature for feedlot finishing lambs (Jolly and Wallace 2007) and finishing lambs on pasture (De Brito et al. 2017) shows very little difference between the practices. Lamb growth rates ranged from -51 to 409 g/day with a mean of 209 g/day for feedlot finished lambs (Jolly and Wallace 2007) whereas lamb growth rates ranged from 109 to 387 g/day with a mean of 218 g/day on pasture (De Brito et al. 2017). In reality, there are too many factors influencing lamb growth rates within studies for comparisons to be made between experiments but these reviews highlight the diversity of lamb growth rates regardless of finishing treatment.

If hypothetically nutrient supply in confinement and at pasture were equal, feeding lambs in confinement would likely increase growth rates due to the reduction in activity energy expenditure associated with grazing and ruminating (Murphy et al. 1994). Additionally, ruminants fed high-concentrate diets generally have smaller gastrointestinal tracts (Priolo et al. 2002); however, this is dependent on the composition of the diet and level of feeding. Both reduced activity and smaller digestive organs results in a reduction in heat production energy losses and consequently increased energy availability for liveweight gain (Oddy et al. 1997). Irrespective of the feeding environment or diet, it is clear that lamb growth rates are a product of mature weight, nutrient intake and heat production energy costs.

9.1.3 The development of the rumen

A review of the development of the gastrointestinal tract in ruminants identified that improvements in the management of the weaning transition could decrease mortality, disease susceptibility and increase post-weaning growth (Baldwin et al. 2004). Ruminants are essentially born as monogastrics and initially rely solely on the nutrients supplied from colostrum and maternal milk to meet their energy demands for maintenance and growth (Baldwin et al. 2004). The act of suckling activates the reflexive closure of the oesophageal groove at the intersection of the oesophagus and reticulum which allows milk to escape ruminal fermentation and directly enter the abomasum to be absorbed in the intestines (Orskov et al. 1970).

As the ruminant develops, it must adapt from its reliance on milk to develop viable ruminal fermentation thus enabling the conversion of solid feed to absorbable nutrients to meet their energy requirements (Baldwin et al. 2004). The contribution of milk to total dietary energy intake decreases up until weaning when it is completely removed from the diet. The major determining factor for when natural weaning occurs is the milk yield of the dam (Arnold et al. 1979). The ewe-lamb bond has shown to weaken rapidly as early as two months following birth as this bond is highly dependent on the ewes' milk production which is contingent on available nutrition (Arnold et al. 1979).

To increase productivity in animal production it is usually necessary to wean prior to natural weaning to allow the dam to recover for further reproduction and to better partition available feed resources (Furnival and Corbett 1976). In the case of dairy calves, which are removed from their natural mother at birth and hand-reared, it is of substantial economic advantage to transition them to a grain-based diet as early as possible as it reduces both labour and feed costs (Khan et al. 2016). It is for this reason that most of the literature covering the development of the rumen has been conducted in dairy calves and involves weaning animals at ages younger than six weeks (Meale et al. 2017). More recently, there has been increasing interest in the early weaning of beef calves and lambs, especially in seasons with below average pasture availability, due to the reproductive benefits from maintaining body condition and the ability to better allocate feed resources (Kenyon et al. 2004).

The rumen is physically undeveloped at birth and increases from 30 to 70% of the capacity of the gastrointestinal tract during the weaning process (Warner et al. 1956). Following the initiation of solid feed intake and the subsequent establishment of ruminal fermentation, the rumen undergoes both physical and metabolic development. The physical component can be partitioned into an increase in rumen capacity including increased musculature and motility, and the maturation of the ruminal epithelium including the keratinisation of mucosa and the growth and development of ruminal papillae (Baldwin et al. 2004).

When compared to control animals fed grain and hay diets, ruminants maintained solely on milk during the first weeks of life exhibit minimal ruminal development with respect to rumen weight (Tamate et al. 1962; Hamada et al. 1976), capacity (Smith 1961; Tamate et al. 1962), papillary growth

(Warner et al. 1956; Tamate et al., 1962), pigmentation (Tamate et al. 1962) and musculature development (Warner et al. 1956; Smith 1961; Tamate et al. 1962; Hamada et al. 1976). These results are due to the closure of the oesophageal groove in suckling ruminants that prevents substrate from entering the rumen (Orskov et al. 1970). Inserting ruminally inert materials such as nylon bristles (Warner et al. 1956), plastic sponges (Tamate et al. 1962) and wood shavings (Smith 1961) into the rumen can replicate the physical stimulus of feed in the rumen by increasing capacity and musculature development; however, these materials do not stimulate papillary development.

The fermentation of solid feed results in the production of volatile fatty acids (VFA's) which are predominantly absorbed through the rumen wall and stimulate ruminal papillae development (Warner et al. 1956; Sander et al. 1959; Baldwin et al. 2004; Suarez et al. 2006; Rey et al. 2012). Feeding hay and grain resulted in extensive forestomach development even at just four weeks of age which included papillary growth and the pigmentation of the ruminal mucosa (Tamate et al. 1962). Hand reared goat kids (Hamada et al. 1976) and weaned calves (Stobo et al. 1966) both demonstrated that rumen muscle weight increases in roughage-fed animals, whereas the maturation of rumen epithelium is more response to the intake of concentrates.

The ruminal infusion of VFA solutions of sodium butyrate and sodium propionate have resulted in marked development of ruminal papillae whereas other VFA solutions demonstrated very little change (Sander et al. 1959). It was hypothesised that the development of ruminal papillae is the result of the metabolism of these compounds; however, development in animals where VFA's were directly supplied to the rumen is not nearly as extensive as that seen in ruminants with access to fermentable solid feed (Tamate et al. 1962; Lane and Jesse 1997). Whilst butyrate and propionate have been implicated in improving the development of the ruminal papillae, there is limited evidence of any direct effects (Cavini et al. 2015). It has been concluded that the development of the rumen is highly correlated with the rate of growth of the whole animal (Gilliland et al. 1962; Stobo et al. 1966; Hamada et al. 1976) which is a response to the amount of feed consumed and the energy density of the diet.

Contrary to the physical development of the rumen, it has been discovered that some aspects of the metabolic development of the rumen occur in the absence of solid feed intake and are more closely related to animal age (Bush et al. 1988; Lane et al. 2002; Eckert et al. 2015). Thus, the development of animals over time cannot be eliminated as a causative factor for rumen development despite the large volume of evidence implicating VFA's as the putative trigger. These findings indicated that irrespective of feed intake, ruminants weaned prior to eight weeks of age may not have a rumen as functional as that of a mature ruminant.

9.1.4 The effects of weaning age on lamb growth rates

Conventional weaning of lambs typically occurs when lambs are between 10 and 14 weeks of age (Corner-Thomas et al. 2020). There are several potential advantages from weaning lambs at younger ages, especially if stocking rates are high or feed quality declines. Feed demand can be reduced by selling ewes or restricting their intake, lambs do not have to compete with ewes for pasture and higher quality nutrients can be made available to lambs (Corner-Thomas et al. 2020). In two experiments, both conducted over multiple seasons, lambs weaned at seven and eight weeks of age onto a high quality pasture have shown variable results, when growth rates are compared to lambs that remained with their mothers on a lower quality pasture until weaning at 12 or 14 weeks of age (Corner-Thomas et al. 2020; Ekanayake et al. 2020). In both studies and all years, lambs and ewes that grazed the higher quality pastures until weaning at 12 or 14 weeks of age had faster growth rates and were heavier at weaning. These experiments demonstrate that in certain seasonal circumstances lamb growth rates can be maintained or increased by weaning lambs early and providing higher quality nutrients. However, they also highlight that lamb growth rates will be maximal for lambs weaned at a conventional age provided there is a high-quality feed source for both the ewe and lamb.

Lambs could still be attaining a relatively high proportion of their energy from milk prior to weaning and removing that energy supply will inevitably inhibit maximal growth depending on the milk production capacity of the ewe and the energy requirements of the lamb for their stage of growth. Furthermore, if the ewe’s milk production is high, there would be substantial changes in gut fill and organ mass following weaning as the animal adapts to the change in dietary energy source (Warner et al. 1956). This would have substantial effects on the liveweight change of the animal immediately post-weaning. A shortcoming of the early-weaning experiments is that they compare conventionally weaned lambs at the point of weaning with lambs that have been weaned for several weeks and there is potential for large discrepancies in gut fill mass. Following weaning of the conventionally weaned lambs, their liveweight is likely to change dramatically over the next two weeks as they adapt to the consumption of pasture as their sole energy source.

Experiments conducted by Campbell et al. (2017) weaned lambs early and conventionally but followed both treatments post-weaning through a finishing feedlot phase until slaughter weights were achieved. In both experiments, lambs that were conventionally weaned took the shortest amount of time to reach slaughter weights; however, they also entered the feedlot heavier on both occasions. It is possible that due to gut fill effects, conventionally weaned lambs would have still reached slaughter weights earlier had the lambs entered the feedlot at a similar liveweight as was observed in some years by Corner-Thomas et al. (2020) and Ekanayake et al. (2020). It appears that the early weaning of lambs may not be beneficial for lamb growth rates unless it facilitates an increase in total nutrient supply for the lambs whilst considering that the lambs may still be obtaining nutrients from milk.

9.1.5 The potential for creep feeding to increase lamb growth rates

Creep feeding is the supplementation of young animals still suckling their mothers whilst restricting their mothers from accessing the supplement. Creep feeding is a potential alternative to early weaning lambs as it enables lambs to access improved nutrition and means the energy supplied by milk is still available. The response in liveweight gain of lambs grazing pasture provided with both restricted and ad libitum intake of creep fed supplement was shown to vary between seasons (De Villiers et al. 2002). The average daily gain of lambs during the first season improved with increasing levels of supplement from six weeks of age to weaning. In the second season, a similar trend was observed; however, lambs without access to creep fed supplement had increased growth rates after the peak lactation of their dams. This resulted in weaning weights that were not significantly different between treatments. In the first season, ewe liveweight decreased by between 7 and 12.5% due to lower pasture availability, whereas in the second season, ewes gained in liveweight by 9 to 17%. Despite the ewe weight loss in the first season, lambs without access to creep fed supplement maintained growth rates similar to supplemented lambs for the first six weeks of lactation. This demonstrated the ewe’s ability to mobilise body tissues in favour of milk synthesis to sustain growth of their lambs during this time (Williams et al. 1976) and highlighted that there exists a limit to a lamb’s capacity for nutrient intake irrespective of supply.

Pasture availability has no effect on milk production during the first five weeks of lactation and ewes on higher levels of nutrition and at lower stocking rates have greater milk production thereafter (Gibb and Treacher 1978; De Villiers et al. 1993). Reductions in lamb growth rate are therefore most pronounced in the later part of lactation due to declining feed availability and the resultant dwindling milk production (Ates et al. 2017) which means that the effects of creep feeding are unlikely to be observed until the later stages of lactation. When pasture availability becomes restrictive in the later parts of lactation, solid feed intake by their lambs increases rapidly (Penning and Gibb 1979; Morgan et al. 2007). The amount of concentrate consumed by lambs appears to increase as lactation progresses. For example, creep feed intake was minimal initially (15 g/day when lambs were two weeks of age) but increased to 630 g/day in the last week before weaning at 12 weeks (De Villiers et al. 2002). There was no apparent advantage from supplementing at levels higher than 500 g/head/day which the authors postulated to be because lambs were meeting all their requirements for maintenance and growth (De Villiers et al. 2002). Lambs receiving 50% of their energy requirements via infused VFA's showed no improvement in growth rates despite no reduction in the consumption of milk replacer (Lane and Jesse 1997). The milk production of the ewe and availability of pasture are likely to influence the level of creep feed supplementation at which no further growth rate advantage is observed.

It is clear that creep feeding does not always improve weaning weight, as lambs can achieve high growth rates after the peak of lactation when there is high pasture availability (De Villiers et al. 2002). Over two seasons, average intake for ad libitum creep supplemented lambs was 340 and 334 g/head/day, but weaning weight was only significantly greater than control lambs in the first season. The lack of difference between treatments in the second season may be explained by the substitution effect, whereby animals offered a supplement while consuming a forage-based diet substitute grain for grass (Dixon and Stockdale 1999). Rates of substitution are usually higher in ruminants consuming highly digestible feed and lower with poorly digestible feed. The implications of this are that the benefit to total energy intake by creep feeding lambs, or supplementing any ruminant on pasture, is dependent on the quality and quantity of feed already available to the animal. If lambs are theoretically substituting energy intake from grain for energy intake from pasture at a ratio of 1:1, there is no net energy benefit from supplementation and consequently no improvement in growth rate.

9.1.6 Potential constraints on nutrient intake

Selection of terminal lamb sires has focussed on increased growth rates, increased lean content of the carcass and decreased sub-cutaneous fat (Swan et al. 2017). Whilst selection for greater weaning and post-weaning weights has resulted in increased lamb growth rates, it has also increased the mature size of animals which consequently increases the nutrient requirements to facilitate unconstrained growth (Oddy and Walmsley 2013). The capacity of production systems to exploit superior genetics was investigated and it was discovered that lamb growth rates were consistently less than potential. It was concluded that the intake of nutrients, specifically metabolisable energy, is insufficient for lambs to reach their growth potential. A comparison of common lamb diets revealed that the composition of these diets are alone unlikely to be responsible. Further to this, it was post-weaning growth that was more consistently constrained (Oddy and Walmsley 2013). If practical measures were implemented to increase the intake of nutrients, lamb growth rates could be expected to increase. Anecdotal reports of lambs achieving average daily gains of 400 g/day and higher appear to be more likely explained by errors in measurement than actual lamb performance (Oddy and Walmsley 2013). The intensive feeding of lambs in feedlots provides the opportunity to offer lambs high quality nutrients with no restrictions on intake and yet lamb growth rates are still not reported near potential (Oddy and Walmsley 2013).

It is assumed that all animals have a desired level of feed intake to meet their energy requirements for maintenance and growth; however, an animal's actual intake is typically much lower than this due to one or multiple constraints (Fernandez-Turren et al. 2020). These can include nutrient availability and diet digestibility, capacity of the digestive system, appetite, familiarity and palatability of the feed source and stress (Allen 2014; Illius and Jessop 1996; Burritt and Provenza 1997; Jongman et al. 2017). If the desired level of intake is not constrained it is assumed that genetic potential will be realised (Whittemore et al. 2013). Forages of low digestibility place constraints on intake due to slow clearance from the rumen and passage through the gastrointestinal tract. Highly digestible feeds can be eaten in greater quantities before the physical constraint of capacity applies (Illius and Jessop 1996). Rumen capacity is likely to restrict feed intake when ruminants consume low energy diets or when energy requirements are high (Allen 2014).

9.1.7 Ruminal adaptations to a change in the composition of the diet being fed

The ruminant gastrointestinal tract has evolved to utilise highly fibrous plant materials which have little nutritional value for monogastric animals (Dijkstra et al. 2005). A unique and capacious set of stomach compartments harbour anaerobic microorganisms capable of digesting plant matter to yield VFA's. Of the bacteria present in the rumen, several general types of bacteria can be described based on metabolic functions. Amylolytic bacteria specialize in fermenting starch (from concentrates) whereas fibrolytic bacteria ferment fibre. Stobo et al. (1966) identified that the rumen readily adapts to the diet being fed and there were no permanent effects of the previous diet on the ability to digest an alternate diet. In contrast, Brown et al. (2006) highlighted the importance of the nutritional management of the adaptation period to a high concentrate diet as it can either promote or impair subsequent performance. Bowen et al. (2006) identified that in sheep the main factors responsible for variation in growth rate and the feed conversion ratio were adaptation to diet and the feeding system which includes the presentation and preparation of the feed.

By gradually increasing concentrate supply, populations of ruminal microorganisms can adjust to a ruminal environment with a lower pH so that intake variation and the incidence of acidosis are minimised. An abrupt change from a high-forage to high-concentrate diet can result in subacute and acute ruminal acidosis (Krehbiel et al. 2010). The effects of acidosis can range from a temporary loss in appetite to acute physiological changes that result in death (Brown et al. 2006). Fulton et al. (1979) and Britton and Stock (1987) both observed a decrease in voluntary feed intake by steers with decreased ruminal pH when fed a wheat-based diet.

Current recommendations for adapting sheep and lambs to a high concentrate diet are based upon cattle feedlot adaptation protocols with some allowance for the fact that lambs don't appear to adapt to the feedlot environment as readily as cattle (Oddy and Walmsley 2013). Individual animals vary in their response to adaptation period length and it is likely that current management strategies are based on the responses of the most susceptible individuals and may be conservative for some animals (Brown et al. 2006; Bevans et al. 2005). Whilst most animals could be adapted from a 40% grain diet to a 90% grain diet over three days without inducing acidosis (Bevans et al. 2005), it was discovered that adapting feedlot cattle to a high-concentrate diet in less than 14 days generally results in decreased animal performance over the entire feeding period (Brown et al. 2006). It appears that the successful management of the adaptation period could have greater implications than the prevention of acidosis in susceptible individuals.

Research in dairy cattle has suggested that the ruminal epithelium takes four to six weeks to adapt to concentrate rich diets as the absorptive area increases as well as functional capacity to cope with an increase in VFA levels (Liebich et al. 1987; Bannink et al. 2012; Dieho et al. 2016). The increase in absorptive capacity and morphological development are not necessarily related as it was found that the largest part of increases in absorptive capacity occur within two weeks of a diet change, preceding morphological development (Etschmann et al. 2009). Additionally, microbial changes in the rumen shift from predominantly fibrolytic bacteria to amylolytic bacteria within three weeks (Dieho et al. 2016, 2017; Wetzels et al. 2017). Adaptation to a high grain diet over a period of five weeks led to improved VFA absorption and pH dynamics compared to cattle adapted over a three week period (Humer et al. 2018). These results indicate that whilst a change to a high concentrate diet in under two weeks may not induce acidosis, it could be two or more extra weeks of feeding until the animals have completely adapted to the new diet. Heifers that had been fed a high grain diet for either eight or 34 days prior to the intraruminal infusion of ground barley to induce ruminal acidosis highlighted the potential benefits of increasing the length of the adaptation period. Heifers fed a high grain diet for the extra 26 days exhibited less between day variation in ruminal pH, recovered from induced ruminal acidosis more quickly and had increased fractional rates of VFA absorption (Schwaiger et al. 2013a,b).

A decrease in fractional VFA absorption persisted for up to three months following exposure to an acute bout of ruminal acidosis in lambs (Krehbiel et al. 1995) and the absorption of VFA’s is reduced by 50% in acutely acidotic cattle compared to subacutely acidotic cattle; however, this also reflects the lower ruminal VFA concentrations in the rumen of acutely acidotic cattle due to lower feed intake (Harmon et al. 1985). This demonstrates the importance of slowly adapting ruminants to a high concentrate diet and suggests that the ability of the rumen to absorb VFA’s may be reduced for an extended period following a bout of acidosis. It is recommended that lambs be gradually introduced to grain either by increasing the grain concentration in a total mixed ration or by increasing grain allowance per head in troughs. Despite evidence being scarce for adapting lambs, a minimum 14-day period is recommended to ensure lambs do not suffer digestive disorders (Duddy et al. 2016).

9.1.8 Ruminal requirements for the provision of fibre

It is recommended that lambs are provided high quality hay at the commencement of the adaptation period to ensure animals begin eating; although, the basis for this recommendation is unknown. It is likely to be to encourage high fibre intake to help lambs maintain rumen pH (Humer et al. 2018) and provide an energy source when concentrate intake is low. Lower quality roughages can then be substituted during the adaptation period but should only be included at 10-15% of the ration as they reduce the energy content of the ration and can constrain feed intake (Duddy et al. 2016).

High concentrate diets are palatable and rapidly fermentable stimulating microbial growth and generating large amounts of VFA’s (Aschenback et al. 2010). Dairy cows require concentrate rich diets to meet their high nutritional needs during lactation; however, these diets can impair rumen health by inducing subacute ruminal acidosis. Intermittent declines in ruminal pH affects rumen function and physically effective fibre is required to stimulate chewing activity and salivary buffer supply, rumen motility, and to maintain appropriate functioning of the rumen ecosystem (Allen 1996; Zebeli et al. 2012).

Total mixed ration (TMR) or partially mixed ration feeding is commonly used in dairies as it presumes simultaneous intake of forages and concentrates, thereby smoothing the daily fermentation pattern, avoiding periods of excess fermentation activity and the resultant rapid declines in ruminal pH (Humer et al. 2018). The inclusion of physically effective fibre in TMR's also has disadvantages, most notably, it reduces diet digestibility and the potential intake of rapidly fermentable carbohydrates along with the increased costs associated with storage and handling (Dixon and Stockdale 1999; Nagaraja and Lechtenberg 2007).

Access to chopped lucerne hay tended to increase starter pellet intake prior to weaning for four weeks old lambs and significantly increased concentrate intake, rumen weight and liveweight post weaning (Yang et al. 2015). Similarly, the supplementation of a starter pellet with straw promoted solid feed intake prior to weaning dairy calves at seven weeks of age and post-weaning until experiment conclusion at nine weeks of age (Terre et al. 2015). The provision of a forage source to young calves increased feed intake prior to weaning at seven weeks of age and post-weaning until 10 weeks of age without impairing the digestibility of the diet (Castells et al. 2012). It must be noted that control animals in these studies had no access to any fibre source which isn't typically the case for lambs extensively reared on pasture; however, competition for feed with ewes when supply is limiting has been identified as one important reason to consider early weaning lambs (Corner-Thomas et al. 2020) meaning there is potential for fibre provision to be of benefit on pasture in certain scenarios.

The Australian feeding standards recognises that the inclusion of fibre in an otherwise all-concentrate diet increases feed intake resulting in increased liveweight gain (CSIRO 2007). Recommendations are for 20% of the diet DM to be in the form of roughage; however, this is predominantly based of experiments in cattle. It is recommended by the NRC (2007) that a minimum of 25% of a lamb diet must comprise of neutral detergent fibre (NDF), of which, 75% must be forage fibre. Similarly, it appears this recommendation is based upon the requirements of dairy cows to avoid milk fat depression.

Pereira et al. (2022) investigated five differing levels of NDF in diets fed to lambs to develop more appropriate recommendations for lambs. Dry matter intake was reduced with both the lowest NDF content (20%) and the highest NDF contents (greater than 45%). High NDF contents restrict intake due to their filling effect in the rumen and low NDF diets increase the risk of subclinical acidosis potentially reducing intake; however, dry matter digestibility was greatest with the low NDF diet suggesting that digestive disorders were minimal. It was concluded that lambs require an NDF content of approximately 30% as maximal average daily gain and an improved feed conversion ratio were observed at this level. This is likely because of the observed increase in feed intake at this proportion of NDF inclusion; however, the reason for the increased feed intake is unclear. The exploration of ruminal pH parameters at differing NDF inclusions may have been advantageous but regardless more research is necessary exploring different forage types and degree of fibre processing for improved recommendations for lambs being fed a high concentrate diet.

9.1.9 Prior exposure to feedlot diet and environment

Lambs provided a novel feed source demonstrated decreased intake in comparison to a familiar feed with the effect exacerbated in an unfamiliar environment (Burritt and Provenza 1997). Additionally, by exposing lambs to grain in the presence of their mothers, grain intake was improved post weaning (Lynch et al. 1983). By exposing lambs to a feedlot pellet on two occasions prior to weaning, Savage et al. (2008) identified a greater percentage of lambs eating immediately following feed delivery in the first week in a feedlot compared to lambs that weren't previously exposed to the diet. Contrary to the findings of Burritt and Provenza (1997), there were no differences in feed intake or liveweight gain during the feedlot phase despite an increased number of previously unexposed lambs not consuming the diet in the first two days. Lambs were fed in pens of 20 and overall mean intake in the feedlot was low (1.1 kg/day) (Savage et al. 2008) possibly indicating there was a constraint on intake which may have affected results. Lamb growth rates were also highly variable with 26% of lambs recording mean daily weight gains less than 50 g/day and 29% with growth rates above 150 g/day which suggests that some lambs were consuming very little feed within treatment groups. Had intake been recorded in smaller groups or on an individual basis greater differences may have been observed.

A common method used to familiarise beef cattle with a feed source and feeding environment is termed 'yard weaning' whereby immediately following separation from their mothers, calves remain in yards for several days to be fed and regularly exposed to humans. The reported benefits include increased average daily gains, improved resistance to disease and easier handling (Colditz et al. 2006). Results of yard weaning in cattle in experimental studies have been mixed, with Walker et al. (2007) showing benefits to be transitory. There is some evidence that yard weaning cattle improves temperament, reduces the stress of handling, transport and confinement and that good temperament results in increased growth rates and improved health (Fell et al. 1999). However, yard weaning is unlikely to be the only method available to realise these desirable characteristics. Steers that had been yard weaned and trained to eat grain from troughs did exhibit greater feeding activity during the first few days upon entering a feedlot but the reduced feeding activity of untrained animals lasted only a few days (Walker et al. 2007) which is similar to the results of Savage et al. (2008). It appears that the advantages of the now common industry practice of yard weaning cattle that are destined for feedlot finishing has limited supportive evidence and further research may be necessary.

A study in sheep using Merino lambs compared yard and paddock weaning and discovered that yard weaning was not superior to any of the producers' normal paddock weaning practices (Gabb et al. 2012). Yard weaning in this trial involved weaning lambs onto a grain or pelleted diet to which they had minimal exposure prior to weaning. It was not investigated whether yard-weaned lambs would then better adapt to confinement feeding later in life which could be beneficial to the reduction in non-performers commonly encountered in feedlots (Kirby et al. 2004; Jolly and Wallace 2007).

9.1.10 Shy feeders in lamb feedlots

It is estimated that between 5% and 20% of all lambs that enter a feedlot do not adapt to the environment or the feed ration and are referred to as 'shy feeders' (Kirby et al. 2004; Jolly and Wallace 2007). Factors hypothesised to contribute to this include fear of the environment or feed, acidosis, disease and competition with other animals (Rice et al. 2016). Rice et al. (2016) discovered that shy feeders could clearly be classified as they spent less than 30 minutes each day at the feed trough whereas the remaining lambs were at the feed trough for at least an hour each day. Shy feeders were also twice as likely to visit the feed trough when no other lambs were present. Individual characteristics such as entry weight and lamb temperament don't appear to influence the incidence of shy feeders (Rice et al. 2016).

Feed trough length and stocking density have also shown to contribute to the incidence of shy feeders. Jongman et al. (2017) reported a decrease in feed intake with trough space of 4 cm per head compared to 10 cm per head and the proportion of sheep not consuming supplement fed once daily increased from 0 to 31% as trough space decreased from 24 cm to 4 cm per head (Arnold and Maller 1974). There were no effects on the incidence of shy feeding by increasing floor space from 2 m^2 to 5 m^2 (Jongman et al. 2017); however, both Hodge et al. (1991) and McDonald (1986) observed increases in the number of shy feeders with floor space less than 1.5 m^2 per head. Jongman et al. (2017) noted that growth rates were only 150 g/day perhaps indicating that conditions were sub-optimal in the feedlot. High levels of competition generally increases the proportion of non-feeders and dominant animals often consume the largest amount and prevent other animals from consuming their desired levels (Bowman and Sowell 1997). The basis for current guidelines are largely unknown; however, it is recommended that each animal is provided with an area of 5 m^2 and between 15 and 30 cm of trough space when fed in troughs and 3 to 5 cm when fed via self-feeders. It is clear that the factors or combination of factors contributing to the incidence of shy feeders needs further investigation.

9.1.11 Effects of feeding level and diet composition on digestibility

The availability of metabolisable energy from digestible energy of the same feed is greater at a lower level of intake (Graham 1980; Graham and Searle 1982, Margan et al. 1982). Digestibility decreased from 74%, at a low level of intake, to 69 and 71%, at a high level of intake, for Corriedale and Dorset lambs (20-30 kg liveweight) respectively (Graham and Searle 1982). Subsequent research by Margan et al. (1982) with cannulated wether lambs also found that higher planes of nutrition reduced digestibility of nutrients as well as reducing rumen mean retention times (MRT). At lower intake levels, a greater amount of digesta was observed in the rumen and it was postulated that this was due to the pelleted form of the diet as it is not consistent with lambs on poor quality forage diets (Margan et al. 1982).Steers fed a restricted amount of a concentrate diet also had increased gut fill contents when compared to steers fed ad libitum (Sainz et al. 1995). Such a result could be explained by reduced rumen motility in response to decreased intake and a consequent accumulation of undigested material (Blaxter et al. 1956).

These results show that rumen function, the site of nutrient digestion and the supply of nutrients to the tissues are all affected by changes in relative intake and diet composition. Digestion in the rumen due to changes in rumen MRT appears to be the catalyst, which supports the hypothesis of Graham (1980) that with higher intake, proportionately more digestion occurs in the hindgut.

The effect of plane of nutrition on nutrient digestibility appeared to diminish as sheep matured; however, intake per unit of liveweight was lower in older lambs (Graham 1980; Margan et al. 1982) potentially confounding these results. Following the discovery that methane production was lower in five-month-old lambs compared to 10- or 14-month-old lambs (Graham and Searle 1972), it was suggested that the reduction in digestibility was because less mature lambs have relatively smaller rumens (Graham 1980). As a result, the passage of food would be faster and extent of fermentation less. It would then also be expected that lambs of different sizes at a given age would demonstrate differences in methane production, although Graham and Searle (1972) discovered no evidence of this. Irrespective of this, the feeding level and composition of a diet effects diet digestibility and there is limited evidence that more mature sheep have improved diet digestibility in comparison to lambs.

9.1.12 The inclusion of fibre in a high concentrate diet on digestibility

Since grains are almost always more digestible than forages, it might be expected that there is a linear increase in the digestibility of the diet as the proportion of grain is increased; however, evidence suggests this relationship is non-linear. Digestibility of a mixed ration usually increased more slowly than expected based on the digestibility of the dietary components fed separately (Dixon and Stockdale 1999). This is due to the effects of rapidly fermentable carbohydrates on rumen pH and the corresponding reduction in the population of fibrolytic bacteria available for the digestion of fibrous dietary components (Orskov 1999). The rumen pH must be above 6.2 to achieve the optimal conditions for the digestion of roughages (Mould and Orskov, 1984). A reduction in rumen pH below optimum will not only inhibit cellulose digestion but may also reduce feed intake (Orskov 1999; Dijkstra et al. 2005).

Some approaches that can be used to maintain rumen pH near optimum include feeding multiple times per day and by feeding whole grains instead of processed grains (Orskov and Fraser 1975; Orskov 1999; Dixon and Stockdale 1999). In cattle it is known that feeding whole grains depresses the digestibility of the grain in comparison to ground or cracked grains; however, this is not a consequence of feeding whole grains to sheep as they are efficient at fracturing whole grains whilst ruminating (Orskov et al. 1974; Orskov 1987; Dixon and Stockdale 1999).

Processing the fibrous component of the ration by chopping, grinding and pelleting may be one approach to reduce the risks of acidosis, increase feed intake and maintain rumen pH at optimum levels. The passage of grass through the digestive tract increases both with the amount consumed and with increased extent of processing (Blaxter et al. 1956). This is due to the faster passage rate through the digestive tract allowing increased intake before the constraint of rumen capacity on intake is observed. Grinding and pelleting poor-quality hay increased intake by over 80%; however, apparent digestibility is also reduced by pelleting roughages (Wainman and Blaxter 1972). The depression of dry matter digestibility was associated with increased intake with the observed effects being greater for poor-quality grass than high-quality legumes (Waldo 1986). Rations that spend the greatest amount of time in the digestive tract are digested to the greatest extent (Blaxter et al. 1956). There is potential to maximise feed intake by processing the fibrous component of the ration; however, the disadvantage is that by maximising feed intake, the time digesta spends in the gastrointestinal tract is reduced and the digestibility of each unit of feed consumed similarly decreases (Graham and Searle 1982; Margan et al. 1982).

9.1.13 Nutritional interactions with genetics

Selection pressure has been placed on production animals for highly desirable traits for decades resulting in substantial genetic improvement (Emmans and Kyriazakis 2001). The genetic selection of terminal sires in the Australian sheep industry has primarily focussed on increasing growth rates whilst simultaneously decreasing subcutaneous fat and increasing the muscle composition of the carcass. This type of selection has made a significant contribution to improved lamb growth rates whilst also producing heavier and leaner carcasses at younger ages (Fogarty et al. 1997; Banks 1995; Oddy and Walmsley 2013).

The progeny of rams selected for increased rates of lean growth (Lewis et al. 2002) and rams with higher growth rate EBV's (Hall et al. 2002; Hegarty et al. 2006) have increased growth rates. Hegarty et al. (2006) identified that the final live weight of lambs from high growth rate sires was 4.8 kg heavier than lambs from control or high eye muscle depth sires; however, the effects of differing levels of pasture availability were far more influential. The final liveweight of lambs from the high pasture availability treatment were 14.9 kg heavier. Whilst the liveweight advantage of high growth rate sires carried over from weaning, there was no interaction between high growth rate sires and nutrition for post-weaning liveweight gain.

The experiment by Hegarty et al. (2006) demonstrated that the production benefit from investment in high growth EBV sires was only realised by optimising pre-weaning nutrition and highlighted the importance of ewe condition at lambing. It appears there was a constraint on the expression of genetic potential post-weaning in the experiment by Hegarty et al. (2006) perhaps due to the decline in pasture quality and quantity requiring the supplementation of the high nutrition lambs.

Nutrition level also had no effect on the expression of a lamb's genetic potential for post-weaning growth in the experiment by Hall et al. (2002). It was concluded that the advantages of using high EBV sires for growth may be reduced when nutrition limits lamb growth. In the experiments by Hall et al. (2002) and Hegarty et al. (2006), growth rates post-weaning were far less than pre-weaning (Table 1) despite the increased pasture supply for the high nutrition post-weaning treatments. This moderated the growth rate advantage of high growth EBV sires and with increased growth rates, the benefits of decades of genetic selection is more apparent.

The benefit from the use of sires selected for high muscle growth persisted beyond weaning in the experiment by Lewis et al. (2002) when lambs were fed a high concentrate diet ad libitum, resulting in a mean difference in average daily gain (ADG) of 56 g/day between selection lines (Table 3). This decreased to a difference of 19 g/day with restricted feeding. It was stated that the benefit of feeding a high concentrate diet was that genetic variation is not constrained by nutrition or maternal effects as it is in a pasture-based system (Lewis et al. 2002). The growth rates of lambs were far greater than those observed by Hegarty et al. (2006) or Hall et al. (2002) (Table 1) indicating that nutrient intake was a lesser constraint in the experiment by Lewis et al. (2002). To make further comparisons it would have been beneficial to have known the quality of the diet and intake of lambs in the pasture-based experiments.

Table 3. The effects of genetic selection for high lean growth on average daily gain (ADG; g/day) and feed conversion ratio (FCR; kg intake: 1 kg gain) when feeding a high concentrate diet to lambs post-weaning both ad libitum and restricted (Lewis et al. 2002)

	Ad libitum feeding		Restricted feeding	
Change in LW[A]	Selected	Control	Selected	Control
24 to 36 kg				
ADG	461	436	226	215
FCR	3.2	3.5	4.1	4.4
36 to 62 kg				
ADG	463	393	317	288
FCR	5.2	6.0	5.7	6.5
62 to 107 kg				
ADG	271	198	210	193
FCR	9.7	11.5	9.7	10.4
Overall (24 to 107 kg)				
ADG	398	342	251	232
FCR	6.0	7.0	6.5	7.1

[A] Mean liveweights of males and females

An important finding from the experiment by Lewis et al. (2002) was that lambs from the selected line had an improved feed conversion ratio; requiring reduced feed intake for every unit liveweight gain irrespective of the feeding level (Table 3). The feed intake, growth rates and body composition of lambs from weaning weight selection lines were reported on by both Thompson et al. (1985) and lambs selected for greater weaning weight were discovered to be markedly leaner at similar liveweights. When these results were adjusted for a common age or stage of maturity the proportion of fat, lean and bone was remarkably similar which was in agreement with Butterfield (1988). In addition, at the same liveweight, the lambs selected for increased weaning weight had a greatly reduced feed conversion ratio; however, at the same stage of maturity, both lines had similar liveweight gain per unit of feed intake.

This still fails to explain the results of Lewis et al. (2002) as it was stated that the differences in the feed conversion ratio existed at similar stages of maturity (Table 3). Contrasting the selection for growth alone, the benefit from selection for increased muscle deposition remains irrespective of nutrition level (Lewis et al. 2002; Hegarty et al. 2006) which may provide a potential explanation. Selection for sires with increased muscle depth would, in theory, increase mature weight and alter the mature body composition of the lamb in favour of muscle (Cameron and Bracken 1992; Cameron 1992). As a result, at each stage of maturity, lambs from lines selected for increased muscle deposition would contain greater amounts of lean tissue and be depositing proportionately more protein. Whilst constant protein degradation significantly reduces the theoretical energetic efficiency of protein accretion, the deposition of lean tissue requires less energy intake in comparison to fat due to the lower energy content of protein per unit of weight and the relatively high water content of lean tissue (Oddy and Sainz 2002). Had the experiment by Hegarty et al. (2006) also measured the nutrient intake of lambs, it may have been observed that the progeny from sires selected for increased eye muscle depth also had an improved feed conversion ratio.

9.1.14 The effects of protein supply on the composition of gain

Low or high protein diets were fed ad libitum to six-week-old lambs and once lambs had attained 28 kg liveweight, some lambs were changed from the low to the high protein diet (Orskov et al. 1976). Lambs fed low protein diets contained more fat in the empty body than those on high protein diets. Lambs fed high protein diets had increased rates of liveweight gain (353 g/day) compared to low protein diets but the greatest liveweight gain (164 g/day) was observed in lambs that changed diets from low to high protein (457 g/day) (Orskov et al. 1976). Black and Griffiths (1975) identified that at any liveweight and level of intake, nitrogen retention increases with nitrogen intake to a point before plateauing. To elicit a response to additional protein supply above this plateau requires increased energy intake.

It was identified that lambs can also maintain or continue growing lean tissue whilst in negative energy balance at the expense of body fat, provided that sufficient dietary protein is available (Fattet et al. 1984; Vipond et al. 1989). This means that lambs could potentially be underfed, resulting in a liveweight loss and the depletion of fat reserves, and continue to deposit lean tissue which was proposed as a solution to the supply of overfat carcasses (Fattet et al. 1984). A protein limited diet reduces growth rates and a greater proportion of fat in the empty body whilst when energy supply is limited, fat reserves can be used as an energy source and additional protein can facilitate the maintenance and continued deposition of lean tissues.

9.1.15 The effects of a prior nutritional restriction on the composition of empty body tissue gain

There are several circumstances in which a ruminant's growth path (Figure 2) is altered by the availability of nutrients. In extensive pasture-based farming systems this usually occurs as a result of the seasonal fluctuations of feed supply (Moore et al. 1997). Nutritional restrictions can exist in many forms but ultimately, they either constrain nutrient intake or are a result of a reduction in the nutrient density of the feed source (Ball et al. 1997). Animals that are re-fed after a period of nutritional restriction often exhibit faster growth that requires less feed than is normal after nutrition improves, which is frequently termed 'compensatory growth' (Hogg, 1991). Compensatory growth has; however, proven to be somewhat unpredictable with many factors such as the severity, nature and duration of the restriction, along with the animal's stage of maturity and the quality and quantity of available feed during refeeding all likely contributing to disparities (Sainz et al. 1995; Ball et al. 1997). The improved utilisation of feed for growth and the carcass composition can also be manipulated through varying the quantity of feed provided or by altering the feed constituents. Research describing the body composition of ruminants has identified that following a restrictive period and refeeding, animals can be leaner, fatter or exhibit similar tissue deposition to that expected during normal growth (Ball et al. 1997).

Feed restrictions can be categorised into circumstances where growth is reduced relative to normal growth, the animal is held at maintenance or the restriction results in weight loss. Feeding at a level above that required for maintenance but restricting energy supply below what is required for maximal growth results in a decline in the proportion of fat in the gain (Bass et al. 1990). For animals that are fed to maintain liveweight or at a level that is insufficient to maintain liveweight, the most notable change is usually the decline in the mass of visceral organs resulting in a reduction in the amount of energy required to maintain liveweight due to the decreased heat production of the visceral organs (Ortigues and Durand 1995; Ball et al. 1997). If, despite a reduction in visceral organ mass, maintenance requirements are not met by energy intake, energy stored as fat is then mobilised and utilised to offset the energy deficit.

Searle et al. (1979) exposed lambs at 25 kg liveweight to a 21-week period of undernutrition. The lambs returned to a live weight of 17 kg, and the composition of gain during refeeding was determined to be similar to that of the uninterrupted growth (Searle et al. 1972). Similar observations were made with an experiment using heavier lambs re-fed from 26 kg to 45 kg after losing 25% of their body weight (Drew and Reid 1975). Small differences in the composition of gain were observed between continuously grown and re-fed lambs, especially during the initial stages of regrowth. The immediate regrowth was very rapid and consisted almost entirely of lean tissue which was later confirmed by Thatcher and Gaunt (1992). Following the initial rapid regrowth, weight gain increments were similar in chemical composition to continuously grown sheep (Drew and Reid 1975). It appeared that fat deposition was principally controlled by the animal's weight as a proportion of their mature weight.

This concept was challenged when lambs were restricted to maintain liveweight before being re-fed (Hodge and Star 1984; Thatcher and Gaunt 1992). Lambs that were continuously grown contained significantly more fat at slaughter; however, differences in fat status were less apparent as the carcass weight of the re-fed lambs increased. Rapidly growing lambs contained the most fat and least protein at the start of a finishing phase compared to lambs fed for slow or moderate growth (Turgeon et al. 1982). It was discovered that the slower the growth rate prior to the finishing phase, the greater the response in weight gain and improved feed conversion ratio during the finishing phase (Turgeon et al. 1982; Thatcher and Gaunt 1992). It was hypothesised that the conflicting findings may have been due to the duration of the refeeding period prior to slaughter as it appears that, provided the period of refeeding is of sufficient length, the composition of the re-fed lamb returns to that of uninterrupted growth (Thatcher and Gaunt 1992: Ball et al. 1997).

9.1.16 Explanation of compensatory gain

Cattle that are destined for finishing in a feedlot usually go through a slower growth (backgrounding) phase for the period between weaning and the start of finishing (Sainz et al. 1995). The slow growth phase allows development before fattening and, as a result, cattle contain less fat upon entering the feedlot and demonstrate compensatory gain when provided a high-quality diet (Wilkins et al. 2009). Animals entering the feedlot attract premiums if buyers perceive that they have undergone nutritional restrictions because their subsequent performance is expected to be superior (Sainz et al. 1995).

There were no differences in empty body fat weight at the end of a 100-day feedlot period between previously slow and accelerated growth paths (Sainz et al. 1995) possibly indicating that re-feeding was complete and the composition of gain had returned to that of uninterrupted growth (Thatcher and Gaunt 1992; Ball et al. 1997). Complete compensation also occurred in the first 100 days of a finishing period in a cattle study by Robinson et al. (2001); however, only when differences in liveweight were less than 15 kg at the commencement of the finishing period. This indicates that when a restriction is severe enough, complete recovery either doesn’t occur or takes longer than the period investigated in this study.

Similar results have been observed in lambs as the slower the rate of liveweight gain by lambs during a growing phase, the greater the response in growth rate and improved feed conversion ratio in the finishing phase (Turgeon et al. 1982; Thatcher and Gaunt 1992). Rapidly grown lambs in the growing phase were fatter and contained less protein at the start and end of the finishing phase; however, the differences were much smaller at the end suggesting that lambs of different rates of growth were nearing similar body composition (Turgeon et al. 1982). It appears that the composition of gain of a lamb compensating for a prior growth restriction returns to that of an uninterrupted growth path (Thatcher and Gaunt 1992).

The three basic mechanisms responsible for observed compensatory growth are an increase in feed intake of previously restricted animals, reduced maintenance requirements and, a change in the ratio of fat to protein being deposited in the tissues (Ryan et al. 1993). During the first fortnight of re-feeding, both sheep and cattle exhibit very high rates of gain and thereafter growth rates decline with increasing body weight (Graham and Searle 1975). Carstens et al. (1991) concluded that gut fill and the composition of gain accounted for most of the compensatory growth response. Accretion rates of carcass tissues were unaffected by a prior restriction; however, non-carcass protein and water increased significantly for the previously restricted steers. Consequently, the net energy requirements for gain of compensating steers was lower due to the lower energy content of protein accretion (Carstens et al. 1991).

Contrasting this, Sainz et al. (1995) identified that the compensatory gain response was independent of gut fill and changes in the composition of gain were determined to have played a minor (perhaps non-existent) role in the compensatory growth observed. It was suggested that alterations in maintenance requirements may have been an important factor in determining the magnitude of the compensatory growth response as previously forage fed steers had increased maintenance requirements and did not exhibit the weight gains expected from their very high dry matter intake.

The effects of dietary energy supply on the body composition and rate of gain of lambs from two nutritional histories was investigated. At any level of energy intake, previously restricted lambs had higher rates of gain in both carcass and non-carcass components compared to unrestricted lambs. Lambs that changed from low to high feeding levels demonstrated an improved feed conversion ratio and slaughter data confirmed that this response was not a result of increased gut contents (Hegarty et al. 1999). The improved feed conversion ratio was due to the rate of protein gain being greater in previously restricted lambs, whereas the rate of fat gain was unaffected by nutritional history.

These results may have occurred due to a reduction in maintenance energy requirements in previously restricted animals (Oddy et al. 1997) or there may have been some improvement in the efficiency of the utilisation of energy for gain (Graham 1980). Hegarty et al. (1999) added another potential explanation for the compensatory growth response by suggesting that nutritional history may have changed the energetic efficiency of carcass protein deposition. However, it was acknowledged that estimates of maintenance energy requirements were likely in error as lambs were continuing to deposit protein and fat when predicted energy available for growth was zero. Regardless, nutritional history will need to be accounted for when formulating standards for future feeding systems and growth models.

9.1.17 The efficiency of energy utilisation for maintenance and growth

The efficiency of energy utilisation for gain is calculated by subtracting estimated maintenance energy requirements from metabolisable energy intake and comparing the ratio of energy available for gain and the energy content of the retained energy in the empty body. The energy content of body weight gain is calculated from the sum of the energy retained in protein (23.8 MJ/kg) and that retained in fat (39.6 MJ/kg) (NRC 1981). The improved feed conversion ratio of lambs that have experienced a nutritional restriction or switched from a low to high protein diet was predominantly attributed to the difference in the composition of gain (Orskov et al. 1976; Hegarty et al. 1999); however, these authors also suggested that the efficiency of the utilisation of metabolisable energy for gain had improved. Additionally, it has been shown that the energy utilisation for gain increases with an animals’ stage of maturity (Graham 1980).

A single term for the efficiency of energy utilisation for gain is potentially problematic as the composition of tissue gain changes with stage of maturity or due to nutritional history. Fat has a greater energy content per unit of mass in comparison to protein and lower rates of turnover (Oddy and Sainz 2002); therefore, as the proportion of fat being deposited increases in the empty body, the efficiency of energy utilisation for gain is likely to improve. It has also been conceded that there is considerable uncertainty with how to specify maintenance energy requirements which could be confounding results (Graham 1980; Hegarty et al. 1999).

Maintenance is a term commonly used to describe the feeding level when metabolisable energy intake is exactly balanced by heat production or when retained whole body energy equals zero (Oddy and Sainz 2002). It has little relevance to immature growing animals other than a useful way of calculating the energy not utilised for growth. Several methods have been used to determine an animals’ maintenance requirements such as feeding at a level estimated to maintain live weight and feeding animals at levels above and below estimated maintenance to calculate the requirements for zero energy retention from the difference (Graham 1967). Due to the laborious nature of these experiments, researchers have attempted to accurately define an animals’ maintenance requirements using simple parameters.

Difficulties arise as maintenance energy requirements alter with varying planes of nutrition because of the effects of nutrition on the weights of highly metabolically active visceral organs of which the liver and gastrointestinal tract make the most significant contribution (Ferrell 1988; Johnson et al. 1990; Ortigues and Durand 1995). Ferrell (1988) and Johnson et al. (1990) suggested that about 20 to 25% of total heat production can be attributed to each of these organ systems; however, variations exist depending on nutritional status and physiological state. At maintenance feeding levels, the gastrointestinal tract contributed 30.9% to heat production in adult ewes whereas the liver contributed 25.5%. At half-maintenance feeding levels these values were 26.8 and 20.5% respectively (Ortigues and Durand 1995). The results of Ortigues and Durand (1995) indicate that when feeding above maintenance, the combined gastrointestinal tract and liver contribute to at least 50% of heat production and the contribution is likely to be greater with increasing feeding levels.

The visceral organs have a substantially greater specific rate of heat production than muscle which contributes 13.8% at maintenance and 18.3% at half maintenance feeding (Ortigues and Durand 1995). As a result, the heat production of a ruminant is mostly influenced by the proportion of highly metabolically active visceral tissues relative to muscle mass (Eisemann et al. 1996). The liver is highly responsive to changes in metabolisable energy intake and the gastrointestinal tract is highly responsive to dry matter intake and combined they contribute approximately 70% to total viscera mass (Hegarty et al. 1999; Dougherty et al. 2022).

The current method of specifying maintenance energy requirements is based upon animal characteristics, the energy density of the diet and metabolisable energy intake (CSIRO 2007). Whilst this method is supported by data from multiple studies, there are many circumstances where it is problematic. Most notably, when animals have experienced a prior nutrition restriction as there is a lag as the visceral organs and resultant heat production increase in response to a more nutrient dense diet (Burrin et al. 1990).

9.1.18 Feeding systems to model lamb growth

Current feeding systems use nutrient supply and animal characteristics to predict animal growth but cannot accurately predict body composition or make allowances for the effects of nutritional history (Oddy et al. 2019). Oddy et al. (1997) proposed a solution by developing a model consisting of two protein pools; a large pool (muscle) with a lower rate of protein turnover and lower energy expenditure and a smaller pool (viscera) with a higher rate of protein turnover and higher energy expenditure. The large pool included carcass muscle, head and feet, skin without wool and blood, and the smaller pool is comprised of the internal organs, heart, lungs and spleen, liver and gastrointestinal tract. Energy not accounted for by heat production or protein deposition was allocated to a single pool representing fat (Oddy et al 1997). With this approach there is no requirement to estimate the efficiency of energy use for maintenance and growth although there is a need to accurately measure heat production.

The viscera accounts for at least half of the animal component of heat production and therefore must be explicitly represented (Oddy et al. 2021) despite being only approximately 10% of empty body protein mass. Moreover, the viscera responds more quickly than carcass muscle or fat to changes in nutrition (Ortigues and Durand 1995).

Comparative slaughter studies have historically been undertaken to investigate energy transactions for the development of the nutrient requirements of ruminants. These studies are laborious due to the extended feeding of animals, the data collection process and laboratory analysis requirements.

Because of their nature, comparative slaughter studies typically comprise a limited number of animals with an even smaller representative cohort slaughtered at the commencement of the experiment for the initial body composition to be determined (Hegarty et al. 1999; Dougherty et al. 2022). Whilst the comparative slaughter of lambs can provide large and detailed datasets for individual animals, due to the reliance of an initial representative cohort, the change in individual animals over time cannot be analysed. This means individual animals within treatments can only be fed one feed type at one feeding level for meaningful data to be collected.

A non-destructive method for the analysis of body composition would alleviate several limitations of comparative slaughter. The advancement of medical imaging has permitted the CT scanning of live sheep which has proven capable of accurately analysing carcass composition (Young et al. 1996; Macfarlane et al. 2006; Kvane and Vangen 2006; Haynes et al. 2010) and estimating volumes of empty body components such as the rumen (Haynes et al. 2012; De Barbieri et al. 2015; Bain et al. 2014; Goopy et al. 2014; Bond et al. 2017). CT scanning of sheep has also been used to investigate changes in both the carcass and visceral tissue composition during and after a period of nutritional restriction (Ball et al. 1997).

It is therefore likely that CT scans of live lambs would also be able to inform and further develop predictive growth models by analysing compositional changes in individual lambs over time. Whilst the individual animal detail that comparative slaughter provides is unlikely to be replicated, it may be a suitable compromise to increase the number of animals represented in an experiment whilst simultaneously reducing labour and costs.

9.1.19 Summary

Maximal lamb growth rates are the product of good health, high nutrient intake and low maintenance energy requirements irrespective of the feeding environment. The intake of metabolisable energy is the major constraint on lamb growth rates and if practical measures could increase nutrient intake, lamb growth rates would be expected to increase. The intensive finishing of lambs ensures the continuous supply of high-quality nutrients providing the opportunity to maximise lamb growth rates and avoiding seasonal fluctuations in the quantity and quality of feed supplied by pasture. The adaptation of lambs to a high-concentrate diet has been identified as potentially problematic and the nutritional management of lambs prior to intensively feeding requires investigation.

As lambs advance in maturity, the gross energy required for liveweight gain, diet digestibility and the efficiency of energy utilisation for gain all increase. Similarly, the efficiency of energy utilisation for gain also appears to be improved for animals with a prior nutritional restriction. However, there is some uncertainty surrounding the specification of maintenance energy requirements with current ruminant feeding systems not considering and accounting for the nutritional history of the animals. The separation of visceral organ and carcass lean tissue may improve the understanding of energy transactions in growing ruminants further developing the prediction of nutrient requirements and ruminant growth models. The use of CT scans of live animals presents an opportunity to explore this concept in further detail.

9.2 Outputs and publications

9.2.1 Full papers

a) Keogh, T. P., McGrath, S. R., Oddy, V. H., Hernandez-Jover, M., Dickson, H., & Allworth, M. B. (2022). Are there opportunities to improve lamb feedlot production efficiency? A cross-sectional survey. *Animal Production Science*, *62*(4), 381-391. https://doi.org/https://doi.org/10.1071/AN21309

b) Keogh, T. P., McGrath, S. R., Allworth, M. B. & Oddy, V. H. Submitted to Journal of Animal Science August 2022

c) It is anticipated the 3 more manuscripts will be prepared from this research for submission to applicable journals

9.2.2 PhD dissertation

A PhD dissertation has been prepared and will be submitted for examination in December 2022.

Keogh, T. P. Investigating the constraints on lamb growth in intensive feeding systems

9.2.3 Conference Papers and Abstracts

A) Keogh, T.P., McGrath, S.R., Oddy, V.H., Hernandez-Jover, M., Dickson, H., & Allworth, M.B. (2021). Lamb feedlot cross sectional study: current practices in the Australian lamb feedlot. 33rd Biennial Conference of the Australian Association of Animal Sciences (AAAS 2021). Perth, Australia.

B) Keogh, T.P., McGrath, S.R., Oddy, V.H. & Allworth, M.B. (2021). Nutritional management of lambs prior to feedlot entry can effect feedlot growth rate. 33rd Biennial Conference of the Australian Association of Animal Sciences (AAAS 2021). Perth, Australia.

C) Keogh, T.P., Oddy, V.H., Allworth, M.B. & McGrath, S.R. (2022). Stage of maturity and energy intake level influences protein and fat deposition in cross-bred lambs. 34th Biennial Conference of the Australian Association of Animal Sciences (AAAS 2022). Cairns, Australia.

D) Keogh, T.P., Oddy, V.H., Allworth, M.B. & McGrath, S.R. (2022). The effects of feed intake at two stages of maturity on the body composition of cross-bred lambs. 78th Annual Conference of the British Society of Animal Science (BSAS 2022). Nottingham, United Kingdom.

9.3 CT Scanning Standard Operating Procedure

CT scanning sheep

Recommended instructor to student ratio: 1:6. This is to avoid crowding the animal and space considerations.

Category

3. Minor conscious intervention

Objective

To effectively restrain sheep in a cradle and CT scan sheep, for example to compare body composition (such as fat, muscle, organ size), without need to euthanise sheep

Alternatives to animal use

There are no practical alternatives

Equipment

- Trailer for transporting animals to the CT scanner. If a large number of animals are being scanned consecutively, a second trailer may be used to hold and transport animals that have already been scanned.

- Portable yard panels to ensure animal cannot escape between removal from the trailer and being secured in the cradle

- A cradle suitable for restraining sheep and made of a material suitable for the CT scanner. Cradle includes straps to go over neck, shoulder and hips. See fig. 1 for an example

- CT scanner

Safety and Risk considerations

Enough personnel are available to catch and restrain the sheep, and personnel are strong enough to carry the sheep in the cradle into the CT scanner. Personnel are competent to handle and restrain sheep to minimise danger to self (e.g. ergonomic injuries) and sheep.

All personnel to exit the room during CT scanning to avoid exposure.

Drugs, chemicals or biological agents

No sedative should be required, however if it becomes necessary to sedate then a veterinarian will be contacted and sedative applied. Alternatively, the individual animal will be retired from the process.

Procedure

Sheep are loaded into a trailer for transport from the sheep yards to the VCC

If a large number of sheep are to be scanned, 2 sheep (not to be scanned) are loaded into a second trailer. This is the trailer that sheep will be loaded into after scanning. Having 2 sheep in the trailer already post-scanning will reduce sheep stress post-scanning.

Both trailers taken to VCC and parked in the bay outside of the CT scanning room. Temporary yard panels to be set up behind the trailer.

An individual sheep is caught and removed from the trailer and secured in the cradle, which is positioned within the temporary yard. Two people minimum are required for this procedure. The first person catches the sheep and positions in the sitting position in the cradle and restrains the sheep by keeping downward pressure on the sheep, while the second person secures the straps over the sheep.

Figure 1. Sheep restrained in sitting position in cradle with straps over neck, shoulders and hips

Cradle with sheep carried into room and placed in CT scanner.

All personnel exit room. Scanning commences

Once scanning is complete, cradle with sheep is carried back outside to the temporary yard. Straps removed and sheep loaded into the trailer.

Once all sheep have been scanned and loaded into the second trailer, sheep are returned to the sheep yards.

Impact on wellbeing of animals

Procedures are low impact, non-invasive and are considered normal management of sheep.

Sheep will be handled quietly and impact monitored by visual assessment. Handling by experienced operators will minimise that impact.

CT scanning is a routine diagnostic procedure. Time in CT scanner will be kept to minimum required for scanning as advised by the operator.

Animal Care

Animals will be observed for signs of distress during the procedure. The procedures will be conducted quickly to allow release of animals from the crate, minimising distress. These procedures have no after effect, but animals will be observed immediately after release to ensure normal behaviour.

Pain Relief

Not needed. The procedure should not cause pain.

Reuse and repeated use

Animals are usually measured at periods no more frequently than once weekly, depending on the needs of the investigation.

Qualification, experience or training necessary to perform procedure

Competence in handling small ruminants.

A suitable operator is required to operate the CT scanner