Final report

Effect of short duration lairage on ante-mortem inspection, carcass characteristics, and microbiological status of feedlot cattle during winter conditions

Project code: B.FLT.1022

Prepared by: Annika Alexander
Emma Lynch
Holly Speers
Kara Tighe
Peter McGilchrist
University of New England

Date published: 2025

PUBLISHED BY
Meat & Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

In Australia, cattle typically spend 16-24 hours in lairage and can be without access to feed for longer periods depending on transport time and feed curfews. These periods off-feed can lead to lower carcass weights and increases in the incidence of dark cutting. This project measured the impact of short duration lairage (< 5 hours) compared with normal duration lairage (> 18 hours) on hot standard carcass weight (HSCW), carcass characteristics and microbiological status of 4,632 feedlot cattle in winter conditions across three market categories (domestic, short-fed export and long-fed export). Cattle in the short lairage groups had 2.62 kg ($P < 0.001$), 4.64 kg ($P < 0.001$) and 1.66 kg ($P = 0.044$) heavier HSCWs in the domestic, short-fed export and long-fed export market categories, respectively. Cattle in the short lairage groups had 2.39 kg ($P < 0.001$) and 4.78 kg ($P < 0.001$) heavier cold carcass weights (CCW) in the domestic and short-fed export market categories, respectively. Cattle in the short lairage groups had 0.3% and 0% dark cutting carcasses compared with 1.2% and 2.32% dark cutting carcasses in the normal lairage groups of the domestic and short-fed export market categories, respectively. Microbiological swabs for *Salmonella* spp., *E. coli*, coliform and total viable count (TVC) were under the industry thresholds for reporting for both short and normal lairage groups. This indicates that reduced time for washing in the short lairage period has no negative impact on contamination of carcasses and therefore food safety. The cumulative time off feed, from feedlot to the knock box, is the key determinant negatively impacting carcass weights. The economic analysis indicated that the adoption of short duration lairage practices led to higher gross revenue between $13.65/hd and $44.95/hd across the three market categories investigated. The results of the study will be used to inform best-practice protocols and will ensure improved production efficiency aligns with animal welfare and food safety standards.

Executive summary

Background

In Australia, cattle typically spend 16-24 hours in lairage and can be without access to feed for longer periods, depending on transport time, and farm and/or feedlot feed curfews. This project investigated the effect of reducing the time spent in lairage to less than 5 hours. This project measured the impact of short duration lairage on hot standard carcass weight (HSCW), carcass characteristics and microbiological status of feedlot cattle in winter conditions. This report provides key results for feedlot producers and processors, regulatory authorities, veterinarians, lairage coordinators and transport companies across three market categories. The results of the study will be used to inform best-practice protocols and will ensure improved production efficiency aligns with animal welfare and food safety standards.

Objectives

This project determined the impact of short duration lairage on HSCW, dressing percentage, carcass characteristics and microbial contamination of the animal and carcasses. Food safety was monitored through measurement of microbiological status of the carcasses. These results were evaluated across domestic, short-fed export and long-fed export market categories during winter conditions. Ex-post cost benefit analysis was conducted to determine the economic outcome for the feedlot and processing industries. These results have been communicated to participating stakeholders through presentations, media and publications.

Methodology

A stratified randomised block design was used to compare two lairage treatment groups including short (average 3.5 hours) and normal (average 20 hours) duration lairage. Specifically, this project was completed with 1,980 head of cattle across 15 replicates in the domestic market category, 1,920 head of cattle across 16 replicates in the short-fed export market category and 768 head of cattle across 8 replicates in the long-fed market category (a total of 4,632 individual animals) over a single winter period.

Results/key findings

Reduced lairage duration is both possible and beneficial in large-scale commercial feedlots and within the processing industry. In the domestic market category, short duration lairage resulted in a 2.62 kg heavier ($P < 0.001$) HSCW over normal duration lairage, as well as a 2.39 kg heavier ($P < 0.001$) cold carcass weight (CCW), meaning the difference was maintained through the chilling process.

In the short-fed export market category, HSCW was 4.64 kg heavier ($P < 0.001$) in short duration lairage compared with the normal duration lairage group, as well as 4.78 kg heavier ($P < 0.001$) in CCW. Similar results were observed in the long-fed export market category, were the difference between short and normal duration lairage was 1.66 kg ($P = 0.044$) with short-laired cattle having heavier HSCWs. The proportion of dark cutting carcasses, where pHu > 5.70, was lower in short duration lairage treatment groups in the domestic (0.3%) and short-fed export (0%) market categories compared with the normal duration lairage groups (1.2%, $P = 0.038$ and 2.32%, $P < 0.001$ respectively). There was no difference between treatment groups in the long-fed export ($P = 1.000$) market category.

All microbiological counts (total viable counts (TVC), coliform counts, *E. coli* counts and *Salmonella* spp. detection) on carcasses were below the threshold of concern indicating food safety parameters were not affected by short lairage duration.

Benefits to industry

This project showed that short duration lairage in winter offered a significant benefit in production efficiency and profitability across the supply chain by enabling optimal carcass weights and a reduction in the incidences of dark cutting. HSCWs were 2.62 kg, 4.64 kg and 1.66 kg heavier when cattle were exposed to short duration lairage compared to the normal duration lairage groups for domestic, short-fed export and long-fed export market categories, respectively. This trend followed through to the cold carcass weights in the domestic and short-fed market categories which had 2.39 kg and 4.78 kg heavier carcasses respectively with short duration lairage.

Reducing time off feed and time in lairage also decreases the incidences of dark cutting which is a huge economic cost to the industry. In addition, concerns around food safety associated with short duration lairage during winter conditions have been alleviated. Economic analysis, taking feed costs and dark cutting carcass penalties into consideration, revealed potential gains of $13.65/hd, $44.95/hd and $20.37/hd across the three market categories investigated.

Future research and recommendations

The key recommendation of this study is that time of feed withdrawal before death should be minimised for all grainfed cattle (time between feedlot pen and knocking box). The time spent in novel environments, such as lairage pens should also be minimised. Processing facilities should, where practical, adopt short duration lairage to the largest proportion of the daily kill schedule possible.

The results from this project should be widely disseminated across the lot feeding industry, processing sector, scientific community and should be the focus of a working group with Australian Government on-plant veterinarians to ensure that all veterinarians are up to speed with the implications of unnecessarily long lairage periods.

Future work should focus on the effects of lairage duration on grassfed cattle and sheep. Additionally, current curfew and trucking guidelines for sheep and cattle should be reviewed across all jurisdictions.

Furthermore, a review on the current washing protocols for cattle at processing facilities should be investigated with a focus on minimising washing. Research should continue on ways to clean the cutting lines on the hides of cattle post-mortem to assist with the desire to minimise washing ante-mortem.

Table of contents

1. Background

Lairage is the period of time cattle spend in holding pens at a processing facility after being transported and before entering the knock box. In Australia, this period is usually 12–24 hours and is used by processors to facilitate veterinary ante-mortem inspections, manage logistical coordination for arrival and unloading of trucks, washing cattle, the kill floor schedule and enables time for cattle to recover post transportation and additional time for gut digesta to be excreted (Ferguson et al., 2007; Ferguson & Warner, 2008). The Australian Livestock Processing Industry Animal Welfare Certification System (AAWCS) model code of practice for the welfare of animals recommends cattle be held in lairage for a minimum of 2 hours to rest but in circumstances where the animals have travelled for longer times or are stressed, the time in lairage should be longer (AAWCS, 2024). During lairage, cattle are not generally provided with feed, however, they do have access to water. In addition to time in lairage, cattle are often curfewed, or taken off feed, at the feedlot or pasture prior to transport. In Australia, the recommended guidelines for the maximum curfew time are related to water access rather than feed. These pre-slaughter management processes can result in a cumulative period of time without feed (and potentially water).

Although it is generally accepted that lairage allows recovery from transport stress and logistics of the processing facility, studies have identified a range of events and conditions in lairage that can contribute to stress in the animal; a novel/unfamiliar environment, new noises and change in social structures, food and water deprivation and additional handling (del Campo Gigena et al., 2021; Díaz et al., 2014; Ferguson & Warner, 2008). Lairage environments in Australia can vary from processor to processor, including pen sizes, infrastructure material (metal or wooden), floor material (earthen, rubber and/or concrete), shade provision over pens and washing protocols resulting in inevitable stressful periods. Muscle glycogen can be an indicator of stress and it is well documented that a range of 75 to 120 mmol/kg glycogen in the muscle of cattle and sheep is considered normal (Ferguson & Warner, 2008). Ensuring cattle have adequate muscle glycogen, above a critical threshold of 45-57 mmol/kg (Ferguson & Warner, 2008), at the time of exsanguination is essential for the formation of lactic acid, that depletes muscle pH, overall affecting tenderness, water holding capacity and overall self-life of the product (Ferguson & Gerrard, 2014; Immonen et al., 2000; Loudon et al., 2019). Strategies to reduce both stress and the period of time animals are exposed to stress, such as reducing lairage time and time off feed, may lead to improved animal welfare and carcass characteristics.

Previous research has reported diverse findings following a range of lairage durations. In the Australian autumn, 196 steers on feed for 150 days (84 in one replicate and 112 in another replicate), held in lairage for 18 hours had HSCWs of 1.3 kg less than steers held in lairage for only 3 hours when data from the two replicates was pooled (Ferguson et al., 2007). However this difference was not statistically significant, and it should be noted that cattle were split into their treatment groups only one day prior to slaughter (Ferguson et al., 2007). In contrast, 250 Hereford and Angus steers (530.5 $\pm$ 36.9 kg) in Uruguay were finished on autumn pasture with sorghum supplementation (Clariget et al., 2021). Half were taken off feed 24 hours prior to slaughter, laired for 14 hours and compared to cattle taken off feed 3 hours prior to slaughter and laired for 2 hours, resulting in a 3.7 kg increase in HSCW for the shorter lairage duration (Clariget et al., 2021). Similarly, an Australian study on 400 British-type, grainfed heifers (512.3 $\pm$ 8.3 kg) found that cattle held in lairage for only 1.6 hours had increased carcass weights of at least 3 kg compared with cattle held in lairage for 7.2, 13.0 and 19.6 hours (B.FLT.4002). The authors suggested that cattle slaughtered after 1.6 h lairage had higher carcass weights due to retained muscle glycogen and reduced tissue shrink (B.FLT.4002). A subsequent study with a larger cohort of 2,226 cross-bred steers (739.21 $\pm$ 6.8 kg) fed for 176 days, found that 4 hours of lairage improved HSCW by 7.4 and 6.2 kg, respectively, in comparison to 16.5 or 26.5 hours (B.FLT.4017). The final report concluded that greater stores of liver glycogen were due to the increased carcass weights and acceptable meat colour and ultimate pH when cattle were exposed to 4 hours in lairage compared with 16.5 and 26.5 hours in lairage. Both studies concluded that reducing lairage

duration increased HSCW during summer conditions in Australia which could have financial benefits for the feedlot and processor industries.

Increasing environmental temperatures and solar radiation during summer conditions lead to cattle drinking more water in an attempt to maintain thermoneutrality (Arias & Mader, 2011). However, the combination of the stress from transport and lairage may mean that cattle drink less (Clariget et al., 2021), leading to dehydration in summer, particularly during lairage. In contrast, during winter, cattle tend to drink less due to decreased temperatures and solar radiation (Arias & Mader, 2011), but remain hydrated more easily for the same reasons. Hydration is important for all metabolism but particularly in relation to muscle glycogen and weight of the muscle. Each molecule of muscle glycogen is bound to approximately three water molecules (Fernández-Elías et al., 2015), contributing to the weight of the muscle under normal conditions and the loss of weight when muscle glycogen levels are impacted by stress. Thus, winter conditions may lead to different results when compared to the previous lairage studies due to reduced solar radiation and lower temperatures, enabling cattle to remain hydrated for longer periods.

The impact on meat quality due to lairage conditions should also be considered as there have also been varied reports throughout the literature. Ultimate muscle pH > 5.71, which leads to a 'dark cutting' classification, is often penalised at the point of carcass grading due to inconsistencies in cooking, shortened shelf life and increased microbial growth of meat (Stewart et al., 2024). Ferguson et al. (2007) demonstrated that there was no difference in muscle glycogen (measured at 45 minutes post-slaughter) or ultimate pH of cattle subject to 18 hours of lairage compared with 3 hours of lairage. This result was shown again in a comparison between 2 (3 hours fasting) and 14 (24 hours fasting) hours of lairage for cattle, which did not impact pH (Clariget et al., 2021). In contrast, muscle glycogen was significantly depleted following 12 hours of lairage when compared with 0 hours of lairage for lambs (Díaz et al., 2014). Other parameters such as ossification (an indicator of age and tenderness), marbling, fat depth, eye muscle area, Hormone Growth Promotant (HGP) status and fat colour all contribute to the overall eating quality of a beef carcass (Bonny et al., 2016; Park et al., 2008; Stewart et al., 2024; Thompson, 2004). Most studies, including B.FLT.4017, investigating the impact of lairage durations on these meat quality characteristics do not report any differences (Clariget et al., 2021; Jones et al., 1990).

The microbial status of the carcass is an important consideration when discussing lairage duration due to its role in food safety. In Australia, lairage is used as a time to wash cattle in an effort to reduce dags, dirt/mud and microbial populations on hides prior to cattle entering the slaughter floor. Studies have shown that time in lairage can increase the prevalence of microbes such as *Escherichia coli* (*E.coli*) and *Salmonella* species on cattle due to animal to animal contact, as well as animal to lairage yard surface contact (Collis et al., 2004; Small & Buncic, 2009). Pre-slaughter stress can also impact microbial spread via increased shedding by the live animal (Bach et al., 2004; Barham et al., 2002). High contamination sites for transfer of microbes from the hide to the carcass on the processing line include skin-opening cuts and hide removal (Antic et al., 2010). Washing cattle is one intervention strategy that is used in Australia to reduce the visible microbial load and dirt/mud on the hides of cattle prior to entering the kill floor. The risk of transferring microbial loads to the carcass from washed hides following slaughter and processing is thought to be reduced, particularly for those high contamination risk sites (Antic et al., 2021). High levels of rainfall have been associated with increased microbial shedding in cattle (Lammers et al., 2015; Williams et al., 2015) and industry surveys have indicated that during winter, cattle coming from feedlots might have higher mud scores and/or dags during prolonged wet pen conditions which affects coat cleanliness (B.FLT.4017). They suggest that reducing lairage time would reduce the ability to effectively wash the cattle prior to slaughter (B.FLT.4017). A recent study provided evidence that short duration lairage is safe, reporting no *Salmonella* spp. and no difference in *E. coli* counts for hide on or carcass samples between 4, 16.5 or 26.5 hours of lairage (B.FLT.4017). Although, this study was conducted through the summer months, and the authors suggested that during winter, coat cleanliness and dag scores would be impacted by

weather conditions and may increase the risk of carcass contamination unless intervention strategies are applied (B.FLT.4017).

The primary objective of this research was to determine if short duration lairage during winter conditions can provide similar carcass weight benefits to those seen in summer studies (B.FLT.4017 and B.FLT.4002), whilst maintaining carcass food safety standards. A second objective of this research, following industry engagement, was to determine the effects of short duration lairage across a range of common Australian market categories. To this effect, controlled, randomised studies were undertaken to compare duration of lairage in:

- 1,980 cattle across 15 replicates, on feed for approximately 75 days destined for the domestic market,
- 1,920 cattle across 16 replicates, on feed for approximately 125 days destined for the short-fed export market and
- 768 cattle across 8 replicates, on feed for approximately 340 days destined for the long-fed export market.

We hypothesized that 1) short duration lairage would result in heavier carcass weights when compared with cattle exposed to longer lairage durations, 2) that microbial load on the carcass would not be affected by lairage duration and 3) that meat quality characteristics would not be affected by lairage duration.

This project provides the red meat industry; feedlot producers, processing facilities, on-plant veterinarians, food safety regulators and the Australian government, results and data to objectively quantify the effects of short duration lairage during winter on carcass weights, quality and microbiological contamination. These results can be combined with results from previous studies (B.FLT.4017 and B.FLT.4002) to provide the industry with an overview of the effect of short duration lairage across seasonal variation and cattle being supplied to common markets.

2. Objectives

2.1 Research question

Determine the effect of short duration lairage on ante-mortem inspection, carcass characteristics and microbiological status (hide and carcass) of feedlot cattle during winter conditions.

The effect of lairage duration on HSCW, carcass characteristics and microbiological status of feedlot cattle during winter conditions was measured by comparing short duration lairage (3.5 hours) to normal duration lairage (20 hours). Across all market categories, 6,670 cattle were initially enrolled in the whole trial. Following drafting at each feedlot, a total of 4,650 head were used and allocated to one of two treatment groups; 1) short duration lairage or 2) normal duration lairage, across 39 replicates.

2.2 Research scope

Evaluate the practice across domestic, short-fed and long-fed export market categories.

The effect of short duration lairage was assessed in the three market categories (domestic, short-fed export and long-fed export). In the domestic market category (75 DOF), 3,000 head of heifers were initially enrolled in the trial. At drafting, 1,980 heifers were selected and randomly allocated to one of two treatment groups; 1) short duration lairage or 2) normal duration lairage, across 15 replicates. In the short-fed export category (125 DOF), 2,070 steers were initially enrolled in the trial. At drafting 1,920 steers were randomly allocated to one of two treatment groups; 1) short duration lairage or 2) normal duration lairage, across 16 replicates. In the long-fed export category (340 DOF), 1,600 head of cattle were initially enrolled in the trial. At drafting 768 steers and heifers were randomly allocated to one of two treatment groups; 1) short duration lairage or 2) normal duration lairage, across 8 replicates. Animals not meeting the experimental protocol were removed from the trial and retained by the feedlot/s.

2.3 Economic analysis

Conduct ex-post cost benefit analysis to determine the economic impact of implementation for both the feedlot and processing industries.

An economic analysis was conducted using partial budgets and parametric sensitivity analyses to determine the benefit of implementing short duration lairage across the three market categories. The partial budgets and the parametric sensitivity analyses accounted for change in HSCW, feed costs and the extra ration offered to the short duration treatment group. Further extrapolation of the benefits and overall gross revenue was estimated based on industry average (*National Inventory Report*, 2023) numbers of cattle killed in each market category.

2.4 Extension of the results

Extension of the project results to the feedlot and processing industry through presentations, articles and peer-reviewed publication of research results.

The results of this project have been widely communicated in presentations back to the participating feedlots and processors, at the UNE Feeder Steer School, MLA/ALFA Research and Development Symposium and at the Australian Association of Animal Science Conference in 2024. The results from this study will be further communicated and published to the scientific community in the Journal of Meat Science.

3. Methodology

3.1 Animal ethics

This project was conducted with the approval of the University of New England Animal Ethics Committee (ARA 23-048).

3.2 Experimental design

A stratified randomised block design was used to evaluate the effect of short duration lairage on HSCW, carcass characteristics and microbiological status (hide on and on the carcass) of feedlot cattle.

The study compared short duration lairage (3.5 hours) to normal duration lairage (20 hours) across three market categories including a domestic market category, short-fed export category and long-fed export category. In the domestic market category (75 DOF), 3,000 head of heifers were initially enrolled in the trial. At drafting 1,980 heifers were selected within a weight bracket (~140 kg) and randomly allocated to one of two treatment groups by drafting alternately through a race; 1) short duration lairage or 2) normal duration lairage, across 15 replicates. In the short-fed export category (125 DOF), 2,070 head of cattle were initially enrolled in the trial. At drafting 1,920 steers within a weight bracket (~220 kg) were randomly allocated to one of two treatment groups by drafting alternately through a race; 1) short duration lairage or 2) normal duration lairage, across 16 replicates. In the long-fed export category (340 DOF), 1,600 head of cattle were initially enrolled in the trial. At drafting 768 steers and heifers were selected based on a weight bracket (130 kg) and sex, to ensure groups matched in the ratio of sexes, and randomly allocated to one of two treatment groups by drafting alternately through a race; 1) short duration lairage or 2) normal duration lairage, across 8 replicates.

The experimental unit was dispatch pen. At each feedlot, a home pen of cattle was weighed and drafted according to weight into the two treatment groups which were based on the number of cattle that could fit on one B-double truck. These treatment groups were also termed the dispatch pen. Any cattle not allocated to a treatment group based on weight (too light or too heavy) were excluded from the trial and returned to feedlot pens.

3.3 General

The cattle were fed and housed at three commercial feedlots located in Northern New South Wales (domestic market category) and southern Queensland (short-fed export market category and long-fed export market category). They were processed in commercial processing facilities in Northern NSW and Southern Queensland.

3.3.1 Domestic market category

The heifers for the domestic market category were *Bos taurus* breeds, predominantly Angus, Hereford, Shorthorn, Charolais and Limousin. A total of 3,000 heifers with an induction weight of 357.7 kg ($\pm$ 30.0 kg) were initially enrolled into the study. At the time of induction, heifers were implanted with two Synovex H (200 mg testosterone propionate and 20 mg estradiol benzoate). Cattle were fed a wheat based tempered grain ration offered *ad libitum* with one delivery per day, 100% of the ration offered at approximately 10:00 providing enough feed to last through to the following day. The average number of days on feed was 75.

Five days prior to slaughter, a home pen of 200 head was brought to the yards and weighed to select pens of cattle within a weight bracket (~140 kg). Cattle within the weight bracket were randomly

drafted alternately into one of the two treatment groups 1) short duration lairage (SHORT) and 2) normal duration lairage (NORMAL).

a) Short duration lairage (SHORT, n = 66): Depart feedlot at approximately 07:30 on the day of slaughter (Day 0) to spend approximately 4 hours in lairage.
b) Normal duration lairage (NORMAL, n = 66): Depart feedlot at approximately 15:15 on the day preceding slaughter (Day - 1) to spend approximately 24 hours in lairage.

Cattle outside the weight bracket (~140 kg) were excluded from the trial and returned to their home pen. Once the trial cattle were allocated to their treatment groups, they were moved back to new pens, ensuring treatment groups were housed side by side. These pens had a stocking density of 12 m^2 per head with cloth shades (2.9 m^2 shade per head), concrete feed bunks (33.3 cm per head) and water troughs (45 mm per head). Note, cattle were not mixed with new cattle during this period. This process was replicated 15 times to have a total of 1,980 head for the domestic market category.

On Day -1 cattle in the NORMAL treatment group were offered their ration at approximately 10:00 and then were dispatched to the abattoir at approximately 15:15. On Day -1 cattle in the SHORT group were offered 100% of their daily ration at approximately 09:00. On Day 0 cattle in the SHORT group were dispatched to the processing plant at approximately 07:48. Each dispatch pen (n = 66) was transported from the feedlot to the commercial processor in a separate B-Double truck with air bags for approximately 1 hour and a total distance of approximately 74 km.

Cattle were unloaded into allocated processor pens (287 m^2, 4.3 m^2 per head) with similar shade, water allocation and concrete floors. Cattle in the SHORT group were in lairage for an average of 4 hours 49 minutes and cattle in the NORMAL group were in lairage for an average of 20 hours 51 minutes. The cattle remained side-by-side (but not mixed) leading up to the knock box. Cattle were not provided feed during lairage. Cattle received a belly wash in the holding pens (for approximately 5 minutes) and a further hosing, were deemed necessary on visual inspection by the on-plant veterinarian. On each slaughter day replicate, the treatment groups of cattle were assigned randomly to the kill schedule to ensure unbiased processing.

On Day 0, each treatment group of cattle were stunned with a non-penetrative stunner and processed according to Australian industry standards. Electrical stimulation using StimTech technology (Carne Tech, New Zealand), was administered on the landing table (constant low voltage stimulator operating through static electrodes for 12 seconds; Jarvis LVST1B), the bleed rail (Pulse width: 500 µs, pulse period: 68 ms, 15 Hz, 600 mA; Single channel Applied Sorting Low Voltage stimulator) and at the back stiffener (single secondary tapping at 180 V; Steriline Isolation Step Down Transformer). Electronic radio frequency identification, time of stun and body number were recorded. Observed stun time was 14:24 and 14:10 for SHORT and NORMAL treatments, respectively. Observed MSA grade time on Day 1 was 16:22 and 15:25 indicating an average chill time of 25 hours prior to grading.

3.3.2 Short-fed export market category

The steers for the short-fed export market category were mixed *B. taurus* and *B. indicus* breeds, predominantly crossbred (max 50% *Bos indicus*). A total of 2,070 steers with an induction weight of 438.4 kg ($\pm$ 35.7 kg) were initially enrolled in the study. At the time of induction, steers were implanted with a Revalor H (200 mg trenbolone acetate and 20 mg beta oestradiol) and a Revalor XR (200 mg trenbolone acetate and 20 mg 17β oestradiol – delayed and extended release). Cattle were fed a tempered, rolled and milled grain ration offered *ad libitum* with two deliveries per day, 40% at 08:30 and 60% at 13:00. The average number of days on feed was 125.

On Day 9 prior to slaughter, a home pen of 130 head was brought to the yards and weighed to select cattle within a weight bracket (~220 kg). Cattle within the weight bracket were randomly drafted

alternately into one of the two treatment groups 1) short duration lairage (SHORT) and 2) normal duration lairage (NORMAL).

a) Short duration lairage (SHORT, n = 60): Depart feedlot at approximately 10:20 on the day of slaughter (Day 0), to spend approximately 4 hours in lairage.
b) Normal duration lairage (NORMAL, n = 60): Depart feedlot at approximately 16:15 the day preceding slaughter (Day – 1), to spend approximately 24 hours in lairage.

Cattle outside the weight bracket were excluded from the trial and returned to their home pen. Once the cattle were allocated to their treatment groups, they were moved back to new pens, ensuring treatment groups were housed side by side. These pens had a stocking density of 10-20 m^2 per head, with concrete feed bunks (45.3 cm per head) and water troughs (83.3 mm per head). Note, cattle were not mixed with new cattle during this period. This process was replicated 16 times to have a total of 1920 head for the short-fed export market category.

On Day -1 cattle in both treatment groups were offered their morning rations at approximately 08:30. Cattle in the NORMAL group were dispatched to the processing plant at approximately 16:15. On Day -1 cattle in the SHORT group were offered their afternoon ration at approximately 13:00. On Day 0 cattle in the SHORT group were dispatched to the processing plant at approximately 10:19. Each dispatch pen (n = 66) was transported from the feedlot to the commercial processing plant in a separate B-Double truck with air bags for approximately 2 hours and a total distance of approximately 110 km.

Cattle were unloaded into allocated processor pens (holding capacity 34 head – 60 cattle split into two adjacent pens with 30 head each) with similar shade, water allocation and pen surface conditions. Cattle in the SHORT group were in lairage for an average of 4 hours 1 minute and cattle in the NORMAL group were in lairage for an average of 22 hours 7 minutes. The cattle remained side-by-side (never mixed) leading up to the knock box. Cattle were not provided feed during lairage. Cattle were washed in groups of 20 head for 1.5 minutes using automatic washers, following the processor's standard operating protocols (SOP). On each slaughter day replicate, the treatment groups of cattle were assigned randomly to the kill schedule to ensure unbiased processing.

On Day 0, each treatment group of cattle were stunned with a pneumatic captive bolt followed by exsanguination. Electrical stimulation using StimTech equipment (Carne Tech, New Zealand) was administered in the box cradle (100 V, 0.1 ms pulse width, 2000 Hz, for 15 s), the bleed section (100 V, 0.2 ms pulse width, 820 Hz, for 15 seconds, 80-100 mA), at the back stiffener (150 V, 3 ms pulse width, 30 HZ, 750 mA) and at the pre-chill stimulator stage (300 V, 15 Hz, 12 seconds, 1000 mA). Carcass side weights over 170 kg received no electrical stimulation. Carcasses were processed according to Australian Industry Standards. Electronic radio frequency identification, time of stun and body number were recorded. Observed stun time was 16:10 and 15:43 for SHORT and NORMAL treatments, respectively. Observed MSA grade time on Day 1 was 10:43 and 9:41 indicating an average chill time of 18 hours prior to grading.

3.3.3 Long-fed export market category

The mixed sex cattle for the long-fed export market category were Wagyu F1s and F2s. A total of 1,600 head of cattle were initially enrolled into the study with an induction weight of 407.3 kg (± 25.9 kg). Cattle were fed a tempered grain ration *ad libitum*, 100% of the ration offered at approximately 12:00 providing enough feed to last through to the following day. The average number of days on feed was 340.

Five to 12 days (Day -12 to Day -5) prior to feedlot exit, two home pens of 200 head each were brought to the yards and weighed to select four pens of cattle within a weight bracket (130 kg). They were further drafted balancing groups for sex.

Cattle within the weight bracket were randomly drafted alternately into one of the two treatment groups 1) short duration lairage (SHORT) and 2) normal duration lairage (NORMAL). Two of the experimental pens were allocated as short duration lairage groups (SHORT) and two were allocated as normal duration lairage groups (NORMAL).

a) Short duration lairage (SHORT, n = 48): Depart feedlot at approximately 06:00 on the day of slaughter (Day 0), to spend approximately 2 hours in lairage.
b) Normal duration lairage (NORMAL, n = 48): Depart feedlot at approximately 14:15 the day preceding slaughter (Day -1), to spend approximately 18 hours in lairage.

Cattle outside the weight bracket were excluded from the trial and returned to their home pen. Once the cattle were allocated to their treatment groups, they were moved back to new pens, ensuring treatment groups were housed side by side. These pens had a stocking density of 14.9 m^2 per head with cloth shading, concrete feed bunks (8.6 cm^3 per head) and water troughs. Note, cattle were not mixed with new cattle during this period. This process was replicated 8 times to have a total of 768 head for the long-fed export market category.

On Day -2 cattle in the NORMAL group were offered their full ration at approximately 12:00, then on Day -1 the ration was topped up in the morning to make sure there was feed in the bunk prior to exit. On Day -1 cattle in the NORMAL group were dispatched to the processing plant at approximately 14:17. On Day -1 cattle in the SHORT group were offered their full ration at approximately 12:00, ensuring there was sufficient ration to retain feed in the bunk prior to exit. Then on Day 0 cattle in the SHORT group were dispatched to the processing plant at approximately 05:52. Each pen of cattle was transported from the feedlot to the commercial processing plant in a separate B-Double truck with air bags for approximately 3 hours and a total distance of approximately 170 km. Observed dispatch was on Day 0 at 5:52, and Day -1 at 14:17 for SHORT and NORMAL treatments respectively.

Cattle were unloaded into allocated processor pens with similar shade, water allocation and pen surface conditions. Cattle in the SHORT group were in lairage for an average of 2 hours 14 minutes and cattle in the NORMAL group were in lairage for an average of 17 hours 53 minutes. The cattle remained side-by-side leading up to the knock box. Cattle were not provided feed during lairage. For washing, cattle received an overhead spray in the holding pens with concrete floors for approximately 30 minutes, and a further hosing, where deemed necessary on visual inspection by the on-plant veterinarian. On each slaughter day replicate, the treatment groups of cattle were assigned randomly to the kill schedule to ensure unbiased processing.

On Day 0, each treatment group of cattle were stunned with a non-penetrative stunner, to meet Halal requirements, and processed according to Australian industry standards. Electrical stimulation was administered at the landing platform using StimTech Multifunctional Immobiliser technology (Coopers Plains, Australia; 120-150V, 100µs pulse width, 0.5ms pulse period, 800mA, 2000 Hz), the bleed section (Applied Sorting Technologies Low voltage stimulator (LVES S/N 160, 22-30V, 500µs pulse width, 200ms pulse period, 200mA, 5 Hz) and at hide pull (Applied Sorting Technologies Electronic Back Stiffener (EBS S/N 150, 375V, 25ms pulse period, 2.7A at peak current delivered for 12 seconds). Electronic radio frequency identification, time of stun and body number were recorded. On Day 0, the observed stun time was 11:06 and 11:03 for SHORT and NORMAL treatments respectively. Observed MSA grade day varied from Day 1 to 2. The average chill time prior to grading was approximately 42 hours for both groups.

3.4 Sampling for microbiological testing

Shortly following exsanguination, 10% of the carcasses were swabbed for further laboratory testing of microbiological status of the hide. The body numbers were noted, and the same carcasses were swabbed once the carcass were entering the chiller. Disposable gloves were worn to collect swabs,

previously hydrated with 30mL sterile 0.1% buffered peptone water, from a 300 cm^2 area including 3 x 100 cm^2 sites including the flank, brisket, and butt (Figure 1) using a Whirl-Pack sponge. A sterile 10 x 10 cm grid template was used to ensure sample area size was accurate. It was sterilised between animals. One side of the sponge was used to sample the flank and brisket and the other side to sample the butt. The area was swabbed with 10 passes vertically and 10 passes horizontally with consistent pressure.

3.5 Microbiological testing

Hide and carcass swab samples were stored at < 4°C to ensure microbiological integrity while being transported to NATA-Accredited Symbio Laboratories (Sydney, NSW and Brisbane, QLD, Australia). Standard total viable plate counts (TVC), coliform counts, *E. coli* counts were analysed on petrifilm and *Salmonella* spp. detection was determined by rtPCR.

3.6 Carcass measurements

HSCW was recorded after evisceration and trimming according to the AUS-MEAT standard carcass trim requirements. After chilling for 25.5 hours (domestic market), 18.5 hours (short-fed export market) or 27 hours (long-fed export market), cold carcass weights were recorded, and chiller assessment was conducted by qualified plant graders. Body number, dentition, eye muscle area, AUS-MEAT meat colour, AUS-MEAT marbling and MSA marbling (of the *M. longissimus thoracis* muscle), MSA Index, fat colour (of the intermuscular fat lateral to the rib eye muscle), subcutaneous rib fat (measured between the 12^{th} and 13^{th} ribs), P8 fat (measured on the rump), ultimate pH and ossification were measured and recorded by a qualified Meat Standards Australia (MSA) grader.

3.7 Statistical analyses

Carcass data for the domestic and short-fed export market categories were analysed as the pen of animals once drafted into treatment groups as the experimental unit. Carcass data for the long-fed export market category was analysed with the individual animal as the experimental unit (due to the lower number of datapoints). Outliers from each parameter (ie. HSCW or dressing percentage) were excluded from each dataset if they were more than 3 standard deviations from the mean, resulting in the use of 1,968 datapoints from the domestic market category, 1,896 datapoints from the short-fed export market category and 768 datapoints from the long-fed export market category. The effect of treatment was analysed using the statistical analysis program R x64 3.5.0 (R-Core Team, 2023, Austria) by running linear mixed-effects models with treatment as the fixed effect (SHORT or NORMAL), pre-transport draft weight as covariate for carcass weight variables and slaughter block as a random effect. The proportion of carcasses classified as 'dark cutters', those with ultimate pH > 5.7, were also assessed by Chi-square test to determine the difference between treatment groups. Statistical significance of the main effects was defined at $P \leq 0.05$ and a trend at $P \leq 0.10$ alpha levels.

Microbiological data was analysed with the experimental unit defined as the individual animal (10% of all carcasses). *Salmonella* spp. was categorised as 'Detected' or 'Not Detected' and differences between treatment groups were assessed using a Chi-square test. Thresholds for concern for *E. coli* and TVC on the carcass have previously been outlined (Department of Agriculture, 2023) and were used to categorise those two variables for the current project (Table 1). In Australia, there is no published industry threshold for coliform counts on carcasses, therefore, coliform counts were categorised as either below 'LOR' (limit of reporting, $\leq$ 0.083 CFU/cm^2) or 'Detected' (> 0.083 CFU/cm^2). Categorical values of *E. coli*, TVC and coliform were also assessed by Chi-square tests to determine the difference between treatment groups. For quantitative analysis, TVC, coliform and *E. coli* counts were log transformed prior to analysis. Least squares means are reported using raw data, however, significance was assessed based on the transformed values.

Table 1. Australian Industry thresholds for counts of *E. coli* and TVC on carcasses, adapted from the Department of Agriculture (2023).

CFU/cm^2	Acceptable	Marginal	Unacceptable
E. coli	0	>0 but ≤20	>20
TVC	≤1000	>1000 but ≤31625	>31625

3.8 Economic Analysis

Financial data from each of the participating processing facilities and feedlots was paired with daily ration quantity and cost, as well as HSCW and carcass pHu status. Data collected included:

- Ration cost ($ per kg Dry Matter, DM)
- Ration fed on Day -1 (kg/hd DM)
- Average HSCW (kg per carcass)
- Number of carcasses pHu $\leq$ 5.7
- Number of carcasses pHu $>$ 5.7
- Price of carcass pHu $\leq$ 5.7, ($ per kg)
- Price of carcass pHu $>$ 5.7 ($ per kg)

Partial budgets were used to evaluate the economic impact of shifting from normal duration lairage to short duration lairage for each market category. Each partial budget assessed the change in site specific feed rations on Day -1, penalties for carcasses that were graded as dark cutters (pHu > 5.7) and HSCW yields to estimate the net change in gross revenue from adopting short duration lairage. Results are estimated on a per 1,000-unit basis ($/1,000 hd). Five equations were used to estimate the gross change in gross revenue when shifting from NORMAL lairage to SHORT lairage across the three market categories:

Equation 1. Total feed costs and feed savings ($/1,000 head), applied to NORMAL and SHORT

Ration cost Day -1 * Ration fed Day -1 * 1,000

Equation 2. Total value non-DC carcasses ($), applied to NORMAL and SHORT

Price per kg HSCW, pHu $\leq$ 5.7 ($/kg) * Average HSCW (kg) * Number carcasses pHu $\leq$ 5.7

Equation 3. Total value DC carcasses ($), applied to NORMAL and SHORT

Price per kg HSCW, pHu > 5.7 ($/kg) * Average HSCW (kg) * Number carcasses pHu > 5.7

Equation 4. Change in gross revenue per 1,000 carcasses ($) Domestic and Short-fed export market categories

(Ration cost Day -1 (NORMAL) + Price per kg HSCW, pHu $\leq$ 5.7 ($/kg) (SHORT) + Price per kg HSCW, pHu > 5.7 ($/kg) (SHORT))

—

(Ration cost Day -1 (SHORT) + Price per kg HSCW, pHu $\leq$ 5.7 ($/kg) (NORMAL) + Price per kg HSCW, pHu > 5.7 ($/kg) (NORMAL))

Equation 5. Change in gross revenue per 1,000 carcasses ($) Long-fed export market category

Ration cost Day -1 (NORMAL) + Price per kg HSCW (SHORT)

—

Ration cost Day -1 (SHORT) + Price per kg HSCW (NORMAL)

A parametric sensitivity analysis was undertaken on each partial budget to ascertain the robustness of the results relative to plausible, simultaneous changes in the quantity of feed delivered (ration in kg DM) and short duration lairage HSCW yield (kg HSCW).

The benefit for implementing short duration on the Australian grainfed cattle industry was estimated by using a 5-year average of Australian cattle slaughter data (*National Inventory Report*, 2023) by days on feed (DOF); 75 days (short-fed), 150 days (mid-fed), and over 250 days (long-fed). Gross revenue calculated in the partial budget were used from each market category (DOF). These calculations in Table 11 represent potential annual benefits from adopting short duration lairage using assumptions of average Australian grainfed cattle volumes per year, per DOF category (*National Inventory Report*, 2023). This extrapolation does not account for other sources of variation such as labour or electricity.

4. Results

4.1 Descriptive statistics

Simple descriptive statistics of weights, carcass variables and grading parameters as well as food safety data, including the mean, standard deviation, minimum and maximum values for the three market categories are presented in Table 2. These results provide an overview of the raw datasets.

4.1.1 Domestic market category

The heifers (n = 1,968) had an average induction weight of 357.69 $\pm$ 30.00 kg (mean $\pm$ standard deviation), were fed for 74.74 $\pm$ 7.85 days, weighed 487.75 $\pm$ 36.24 kg at feedlot exit, and had a dressing percentage of 53.01 $\pm$ 2.21% to produce a HSCW of 258.49 $\pm$ 20.99 kg (Table 2).

4.1.2 Short-fed export category

The steers (n = 1,896) were fed for 125.16 $\pm$ 3.07 days, weighed 668.47 $\pm$ 51.36 kg at feedlot exit, and had a dressing percentage of 56.08 $\pm$ 2.73% to produce a HSCW of 374.63 $\pm$ 31.60 kg (Table 2).

4.1.3 Long-fed export category

The cattle (n = 768) had an average induction weight of 407.25 $\pm$ 25.89 kg (mean $\pm$ standard deviation), were fed for 339.71 $\pm$ 17.79 days, weighed 732.71 $\pm$ 58.15 kg at feedlot exit, and had a dressing percentage of 57.84 $\pm$ 1.63% to produce a HSCW of 423.80 $\pm$ 36.01 kg (Table 2).

4.2 Effect of short duration lairage on carcass weights and other characteristics

4.2.1 Domestic market category

Cattle in the short duration lairage treatment group (SHORT) were taken off-feed at the feedlot at 06:25 on the day of slaughter (Day 0), exited the feedlot at 07:48, arrived at the processing plant at 09:35, spent 4 hours and 49 minutes in lairage, were stunned at 14:24 to yield a total of 6 hours and 12 minutes off feed prior to stun. Carcasses were MSA graded 25.72 hours later at 16:22 the day following slaughter (Table 3).

Cattle in the normal duration lairage treatment group (NORMAL) were taken off-feed at the feedlot at 14:35 on the day before slaughter (Day -1), exited the feedlot at 15:15 and arrived at the processing plant at 16:45, spent 20 hours and 51 minutes in lairage, were stunned at 14:10 on Day 0 to yield a total of 22 hours and 6 minutes off feed prior to stun. Carcasses were MSA graded 24.68 hours later at 15:25 the day following slaughter (Table 3).

The duration of lairage had a significant impact on HSCW ($P < 0.001$). Carcasses from the SHORT lairage treatment were 2.62 kg heavier than carcasses from the NORMAL lairage treatment group. The duration of lairage also had a significant impact on cold carcass weight ($P < 0.001$), kilograms of cold shrink ($P < 0.001$), dressing percent ($P = 0.005$), pH ($P = 0.042$) and meat colour ($P = 0.006$), with a trend towards a significant difference in AUS-MEAT marbling ($P = 0.051$) between treatment groups. Carcasses in the SHORT lairage treatment group were 2.39 kg heavier at the cold carcass weight, had increased cold shrink by 0.21 kg and increased dressing percent by 0.48%. Meat colour and pH were decreased by 0.09 and 0.02, respectively for carcasses in the SHORT lairage treatment group. AUS-MEAT marbling was decreased by 0.13 for carcasses in the SHORT lairage group, although this decrease was not significant.

There was no significant difference between treatment groups for MSA marbling (*P* = 0.159), eye muscle area (*P* = 0.834), rib fat (*P* = 0.179), P8 fat (*P* = 0.768), fat colour (*P* = 0.115), ossification (*P* = 0.322) or MSA index (*P* = 0.415).

The proportion of dark cutters was significantly different between treatment groups with 1.2% detected in the NORMAL treatment group compared with 0.3% detected in the SHORT group (*P* = 0.038, Table 4).

4.2.2 Short-fed export market category

Cattle in the short duration lairage treatment group (SHORT) were taken off-feed at the feedlot at 08:49 on the day of slaughter (Day 0), exited the feedlot at 10:19 and arrived at the processing plant at 12:09, spent 4 hours in lairage, were stunned at 16:10 to yield a total of 7 hours and 21 minutes off feed prior to stun. Carcasses were MSA graded 18.56 hours later at 10:43 the day following slaughter (Table 3).

Cattle in the normal duration lairage treatment group (NORMAL) were taken off-feed at the feedlot at 14:46 on the day before slaughter (Day -1), exited the feedlot at 16:15 and arrived at the processing plant at 17:36, spent 22 hours and 7 minutes in lairage, were stunned at 15:43 on Day 0, to yield a total of 24 hours and 57 minutes off feed prior to stun. Carcasses were MSA graded 17.95 hours later at 9:41 the day following slaughter (Table 3).

The duration of lairage had a significant impact on HSCW (*P* < 0.001). Carcasses from the SHORT lairage treatment were 4.64 kg heavier than carcasses from the NORMAL lairage treatment group. The duration of lairage also had a significant impact on CCW (*P* < 0.001), dressing percent (*P* < 0.001) meat colour (*P* = 0.005), eye muscle area (*P* = 0.005), rib fat (*P* = 0.014), fat colour (*P* = 0.002) and ossification (*P* = 0.032). Carcasses in the SHORT lairage treatment group were 4.78 kg heavier at the cold carcass weight and increased dressing percent by 0.70%. Meat colour was significantly lower in the SHORT lairage group compared to the NORMAL lairage treatment group, however, both within industry norms. Eye muscle area was increased by 2.04 cm^2, rib fat was increased by 0.61 mm and ossification was increased by 2.01 for cattle in the SHORT lairage treatment group. There was a trend towards significance for MSA marbling (*P* = 0.083) and MSA Index (*P* = 0.097) with carcasses in the SHORT lairage group having a 9.10 increase in MSA Marbling and a 0.23 increase in MSA index.

There was no significant difference between treatment groups for cold shrink (*P* = 0.667), pH (*P* = 0.716), AUS-MEAT marbling (*P* = 0.402) and P8 fat (*P* = 0.755).

The proportion of dark cutters was significantly different between treatment groups with 2.3% detected in the NORMAL treatment group compared with 0% detected in the SHORT group (*P* < 0.001, Table 4).

4.2.3 Long-fed export market category

Cattle in the short duration lairage treatment group (SHORT) were taken off-feed at the feedlot at 05:14 on the day of slaughter (Day 0), exited the feedlot at 05:52 and arrived at the processing plant at 08:52, spent 2 hours and 14 minutes in lairage, were stunned at 11:06 and resulted in 5 hours and 52 minutes off feed prior to stun. Carcasses were MSA graded 42.04 hours later at 14:08 two days following slaughter (Table 3).

Cattle in the normal duration lairage treatment group (NORMAL) were taken off-feed at the feedlot at 13:28 on the day before slaughter (Day -1), exited the feedlot at 14:17 and arrived at the processing plant at 18:10, spent 17 hours and 53 minutes in lairage, were stunned at 11:03 on Day 0, to yield a total of 21 hours and 35 minutes off feed prior to stun. Carcasses were MSA graded 42.10 hours later at 14:08 two days following slaughter (Table 3).

The duration of lairage had a significant impact on HSCW (*P* = 0.044). Carcasses from the SHORT lairage treatment were 1.66 kg heavier than carcasses from the NORMAL lairage treatment group. Duration of lairage did not impact any other carcass characteristics (Table 3). However, there was a trend towards significance for dressing percent (*P* = 0.068), MSA marbling (*P* = 0.070) and AUS-MEAT marbling (*P* = 0.077), with cattle in the SHORT lairage treatment group having heavier carcass weights by 1.55 kg, increased dressing percent by 0.19%, decreased MSA marbling by 25.26 and decreased AUS-MEAT marbling by 0.24. There was no significant difference between treatment groups for pH (*P* = 0.100), meat colour (*P* = 0.938), eye muscle area (*P* = 0.767), rib fat (*P* = 0.194), fat colour (*P* = 0.624), ossification (*P* = 0.635) or MSA index (*P* = 0.128).

The proportion of dark cutters was not significantly different between treatment groups 0% detected in the NORMAL treatment group compared with 0.003% detected in the SHORT group (*P* = 1.000, Table 4).

Table 2. Descriptive statistics of pens of study cattle in domestic market category (n = 30, n = 66 animals per pen), short-fed export market category (n = 16, n = 60 animals per pen) and long-fed export market category (n = 16, n = 48 animals per pen), presented on raw dataset.

Variable	Mean	SD	Min	Max
Domestic market category				
Entry weight (kg)	357.69	30.00	263.00	471.00
DOF	74.74	7.85	58.00	133.00
ADG (kg)	1.75	0.39	0.48	3.24
Final liveweight (kg)	487.75	36.24	413.00	637.00
HSCW (kg)	258.49	20.99	202.00	340.20
Dressing Percent	53.01	2.21	44.54	63.50
CCW (kg)	253.98	20.75	198.20	335.60
Carcass Shrink (kg)	4.51	1.17	1.40	33.80
Carcass Shrink (%)	1.75	0.44	0.57	12.69
Time of feedlot exit (Normal)	15:15	0:58	13:45	17:20
Time of feedlot exit (Short)	07:48	0:23	07:00	08:41
Time of stun at abattoir (Normal)	14:10	0:48	11:22	15:17
Time of stun at abattoir (Short)	14:24	0:44	12:00	15:33
Time of grade at abattoir (Normal)	15:25	3:36	10:00	22:45
Time of grade at abattoir (Short)	16:22	3:33	10:00	22:25
Time between stun and grade at abattoir (Normal) (hours)	24.68	3.75	18.30	34.92
Time between stun and grade at abattoir (Short) (hours)	25.72	3.54	18.38	33.00
Duration of time in lairage (Normal) (hours)	20.51	2.01	14.49	23.10
Duration of time in lairage (Short) (hours)	04.49	0.41	03.35	05.50
Duration of time off feed prior to stun (Normal) (hours)	22.06	2.02	16.00	24.25
Duration of time off feed prior to stun (Short) (hours)	06.12	0.39	04.50	07.00
Short-fed export market category				
DOF	125.16	3.07	118.00	196.00
Final draft weight (kg)	668.47	51.36	500.00	834.00
Final truck weight (kg)	674.53	16.69	636.00	708.00
HSCW (kg)	374.63	31.60	172.80	485.40
Dressing Percent	56.08	2.73	26.58	73.76
CCW (kg)	371.36	31.35	171.20	481.51
Carcass Shrink (kg)	3.32	1.47	-26.80	22.20
Carcass Shrink (%)	0.89	0.38	-6.48	5.39
Time of feedlot exit (Normal)	16:15	1:34	14:40	20:06
Time of feedlot exit (Short)	10:19	1:39	7:40	13:00
Time of stun at abattoir (Normal)	15:43	2:10	9:44	18:40
Time of stun at abattoir (Short)	16:10	1:44	11:23	19:26
Time of grade at abattoir (Normal)	9:41	2:12	6:41	18:27
Time of grade at abattoir (Short)	10:43	2:45	7:15	17:53
Time between stun and grade at abattoir (Normal) (hours)	17.95	2.36	14.83	26.95
Time between stun and grade at abattoir (Short) (hours)	18.56	2.51	14.58	28.62
Duration of time in lairage (Normal) (hours)	22.07	1.59	17.14	25.36
Duration of time in lairage (Short) (hours)	04.01	0.54	1.53	5.57
Duration of time off feed prior to stun (Normal) (hours)	24.57	1.51	20.34	27.42
Duration of time off feed prior to stun (Short) (hours)	7.21	0.54	5.13	9.17

Long-fed export market category				
Entry weight (kg)	407.25	25.89	184.00	612.00
DOF	339.71	17.79	319.00	559.00
ADG (kg)	0.96	0.15	0.43	1.36
Final liveweight (kg)	732.71	58.15	590.00	890.00
HSCW (kg)	423.95	35.79	324.00	509.50
Dressing Percent	57.86	1.55	52.97	62.70
Time of feedlot exit (Normal)	14:17	0:26	13:49	15:03
Time of feedlot exit (Short)	5:52	0:38	4:33	6:37
Time of stun at abattoir (Normal)	11:03	1:36	8:25	13:10
Time of stun at abattoir (Short)	11:06	1:31	9:10	12:50
Time of grade at abattoir (both)	14:08	2:28	8:18	15:41
Time between stun and grade at abattoir (Normal) (hours)	42.10	14.33	19.13	53.62
Time between stun and grade at abattoir (Short) (hours)	42.04	14.52	19.97	54.02
Duration of time in lairage (Normal) (hours)	17.53	2.19	13.25	20.00
Duration of time in lairage (Short) (hours)	2.14	1.14	0.40	3.35
Duration of time off feed prior to stun (Normal) (hours)	21.35	1.51	19.05	23.40
Duration of time off feed prior to stun (Short) (hours)	5.52	1.09	4.25	7.30

Time: actual time in 24 hours. Duration of time: time presented in hours and minutes.

Table 3. Number of cattle, least square means (±SEM) carcass weights and carcass characteristics for the Domestic, Short-fed Export and Long-fed market categories.

Market category*	Normal	Short	SEM	p-value
		Domestic		
Head of cattle	983	985		
Avg draft weight (kg)	487.49	487.91	3.62	0.786
HSCW (kg)	256.89	259.51	1.37	**< 0.001**
CCW (kg)	252.59	254.98	1.32	**< 0.001**
Carcass Shrink (kg)	4.32	4.53	0.09	**< 0.001**
Dressing %	52.77	53.25	0.30	**0.005**
pH	5.55	5.54	0.01	0.156
Meat colour‡	2.09	2.03	0.02	**0.016**
MSA marbling	419.81	410.69	5.97	0.159
AUS-MEAT marbling	1.69	1.56	0.07	0.051
Eye muscle area (cm^2)	69.98	70.14	0.75	0.834
Rib Fat (mm)	5.48	5.72	0.21	0.179
P8 Fat (mm)	9.72	9.77	0.25	0.768
Fat colour	1.80	1.71	0.07	0.115
Ossification	167.15	164.36	3.08	0.322
MSA Index	55.62	55.83	0.26	0.415
		Short-fed export		
Head of cattle	947	949		
Avg draft weight (kg)	665.45	669.81	5.48	**0.016**
HSCW (kg)	372.14	376.78	0.96	**< 0.001**
CCW (kg)	368.79	373.57	0.92	**< 0.001**
Carcass Shrink (kg)	3.30	3.26	0.17	0.667
Dressing %	55.75	56.45	0.14	**< 0.001**
pH	5.51	5.52	0.03	0.716
Meat colour‡	2.26	2.14	0.10	**0.005**
MSA marbling	309.79	318.89	6.75	0.083
AUS-MEAT marbling	0.66	0.70	0.05	0.402
Eye muscle area (cm^2)	83.80	85.84	0.96	**0.005**
Rib Fat (mm)	7.38	7.99	0.49	**0.014**
P8 Fat (mm)	15.66	15.73	0.45	0.755
Fat colour	0.64	0.46	0.07	**0.002**
Ossification	156.78	158.79	1.27	**0.032**
MSA Index	54.79	55.02	0.14	0.097

		Long-fed export		
Head of cattle	384	384		
Avg draft weight (kg)	731.64	732.08	16.97	0.849
HSCW (kg)	423.12	424.78	1.20	**0.044**
Dressing %	57.75	57.95	0.16	0.068
pH	5.51	5.52	0.02	0.100
Meat colour‡	1.69	1.66	0.04	0.938
MSA marbling	864.64	839.38	14.39	0.070
AUS-MEAT marbling	6.24	6.01	0.13	0.077
Eye muscle area (cm^2)	78.24	78.10	1.11	0.767
Rib Fat (mm)	9.19	9.02	0.49	0.194
Fat colour	0.64	0.65	0.28	0.624
Ossification	173.04	172.66	0.22	0.635
MSA Index	66.71	66.57	0.22	0.128

‡Meat colour was scored as 1A=1.00, 1B=1.33, 1C=1.67, 2=2.00, 3=3.00, 4=4.00, 5=5.00, 6=6.00.

*Data is analysed and presented at the pen level for Domestic and Short-fed Export categories and at the animal level for the Long-fed market category.

HSCW: Hot standard carcass weight, CCW: cold carcass weight, MSA: Meat Standards Australia.

Table 4. Proportions and frequency of Dark Cutters, analysed at the animal level.

Market category	pHu ≤ 5.70	pHu > 5.70	Count	p-value
Domestic				
Normal	98.8 % (971)	1.2 % (12)	983	**0.038**
Short	99.7 % (982)	0.3 % (3)	985	
Sum	99.2 % (1953)	0.8 % (15)	1968	
Short-fed export				
Normal	97.68 % (925)	2.32 % (22)	947	**< 0.001**
Short	100 % (949)	0 % (0)	949	
Sum	98.84 % (1874)	1.16 % (22)	1896	
Long-fed export				
Normal	100 % (384)	0 % (0)	384	1.000
Short	99.74 % (383)	0.26 % (1)	384	
Sum	767	1	768	

4.3 Effect of short duration lairage on microbiological status

In all market categories with swabs collected from the carcass, *Salmonella* spp. was not detected and TVC and *E. coli* counts were well below the threshold of concern (Table 1 for reference numbers). Coliform counts were also below the *E. coli* threshold of concern. The proportions of TVC, *E. coli* and coliform counts and detection of *Salmonella* spp. was not different between treatment groups (Tables 7 and 8).

4.3.1 Carcass results: Domestic market category

There was a significant difference between treatment group TVC results ($P < 0.001$). Carcasses in the SHORT lairage group had higher TVC counts compared to the NORMAL lairage group, 70.02 and 39.10 CFU/cm^2 respectively (Table 5), however, this result is below the threshold of concern (Department of Agriculture, 2023). There were no significant differences in coliform or *E. coli* counts between treatment groups and *E. coli* counts were below the threshold of concern (Department of Agriculture, 2023).

4.3.2 Carcass results: Short-fed and Long-fed export market categories

There were no significant differences in TVC, coliform or *E. coli* counts between treatment groups (Table 5) and all counts were below the threshold of concern (Department of Agriculture, 2023).

4.3.3 Hide-On results: Domestic market category

There were no significant differences in TVC, coliform or *E. coli* counts between treatment groups (see Table 6). *Salmonella* spp. was detected on five hides, two in the SHORT lairage group and three in the NORMAL lairage group (Table 6), but this difference between treatment groups was not significant ($P = 0.981$).

4.3.4 Hide-On results: Short-fed and Long-fed export market categories

There were no significant differences in TVC, coliform or *E. coli* counts between treatment groups (see Table 6).

Table 5. Least squares means (±SEM) for microbiological parameters on the carcass, analysed at the animal level.

Microbial parameters	NORMAL	SHORT	p-value
Domestic market category			
TVC (CFU/cm^2)	39.10 ± 11.29	70.02 ± 11.16	**< 0.001**
Coliform (CFU/cm^2)	0.09 ± 0.01	0.09 ± 0.01	0.604
E. coli (CFU/cm^2)	0.09 ± 0.00	0.09 ± 0.00	0.808
Short-fed export market category			
TVC (CFU/cm^2)	26.02 ± 8.03	37.89 ± 8.01	0.289
Coliform (CFU/cm^2)	0.09 ± 0.01	0.10 ± 0.01	0.514
E. coli (CFU/cm^2)	0.08 ± 0.00	0.08 ± 0.00	0.307
Long-fed export market category			
TVC (CFU/cm^2)	158.30 ± 51.47	40.52 ± 51.46	0.108
Coliform (CFU/cm^2)	0.09 ± 0.01	0.11 ± 0.01	0.524
E. coli (CFU/cm^2)	0.09 ± 0.01	0.11 ± 0.01	0.234

TVC: Total viable count

Table 6. Least squares means (±SEM) for microbiological parameters at Hide-On, analysed at the animal level.

Microbial parameters	NORMAL	SHORT	p-value
Domestic market category			
TVC (CFU/cm^2)	29.18 x 10^5 ± 5.3 x 10^5	28.38 x 10^5 ± 5.3 x 10^5	0.747
Coliform (CFU/cm^2)	402.30 ± 77.74	510.44 ± 77.84	0.110
E. coli (CFU/cm^2)	150.05 ± 33.38	177.33 ± 33.44	0.743
Short-fed export market category			
TVC (CFU/cm^2)	8.09 x 10^5 ± 3.2 x 10^5	10.50 x 10^5 ± 3.3 x 10^5	0.604
Coliform (CFU/cm^2)	1225.22 ± 221.06	1151.78 ± 220.71	0.929
E. coli (CFU/cm^2)	489.76 ± 78.49	522.91 ± 78.21	0.777
Long-fed export market category			
TVC (CFU/cm^2)	11.36 x 10^5 ± 6.07 x 10^5	15.90 x 10^5 ± 6.07 x 10^5	0.216
Coliform (CFU/cm^2)	435.82 ± 189.38	370.89 ± 189.86	0.339
E. coli (CFU/cm^2)	195.99 ± 87.24	232.83 ± 87.62	0.378

TVC: Total viable count

Table 7. Proportions and counts (in brackets) of microbial status on the carcass.

TVC	**Acceptable**	**Marginal**	**Unacceptable**	**p-value**
Domestic				
Normal	99.03 % (102)	0 % (0)	0.97 % (1)	0.225
Short	98.09 % (103)	1.90 % (2)	0 % (0)	
Short-fed				
Normal	100 % (96)	0 % (0)	0 % (0)	1.000
Short	100 % (94)	0 % (0)	0 % (0)	
Long-fed				
Normal	90.24% (37)	9.76 % (4)	0% (0)	0.130
Short	100% (40)	0% (0)	0% (0)	
Coliform	**Detected**	**LOR***		
Domestic				
Normal	9.71 % (10)	90.29 % (93)	-	0.548
Short	13.33 % (14)	86.67 % (91)	-	
Short-fed				
Normal	5.20 % (5)	94.79 % (91)	-	0.737
Short	7.45 % (7)	92.55 % (87)	-	
Long-fed				
Normal	4.88 % (2)	95.12 % (39)	-	0.146
Short	17.50 % (7)	82.50 % (33)	-	
E. coli	**Acceptable**	**Marginal**	**Unacceptable**	
Domestic				
Normal	94.17 % (97)	5.83 % (6)	0 % (0)	0.619
Short	91.43 % (96)	8.57 % (9)	0 % (0)	
Short-fed				
Normal	98.96 % (95)	1.04 % (1)	0 % (0)	0.598
Short	96.81 % (91)	3.19 % (3)	0 % (0)	
Long-fed				
Normal	95.12 % (39)	4.88 % (2)	0 % (0)	0.146
Short	82.50 % (33)	17.50 % (7)	0 % (0)	

*LOR, limit of reporting ($\leq$ 0.083 CFU/cm^2)

Table 8. Proportion and counts (in brackets) of microbial status (*salmonella app., E.coli,* coliform and TVC) on hides.

***Salmonella* spp.**	**Detected**	**Not Detected**	**p-value**
Domestic			
Normal	3.13 % (3)	96.88 % (93)	0.981
Short	2.04 % (2)	97.96 % (96)	
Short-fed			
Normal	0 % (0)	100 % (96)	N/A
Short	0 % (0)	100 % (94)	
Long-fed			
Normal	0 % (0)	100 % (40)	N/A
Short	0 % (0)	100 % (41)	
E. coli	**Detected**	**LOR**	**p-value**
Domestic			
Normal	96.88 % (93)	3.13 % (3)	1.000
Short	95.92 % (94)	4.08 % (4)	
Short-fed			
Normal	96.84 % (93)	3.16 % (3)	1.000
Short	96.77 % (91)	3.23 % (3)	
Long-fed			
Normal	97.56 % (40)	2.44 % (1)	0.192
Short	87.50 % (35)	12.5 % (5)	
Coliform			
Domestic			
Normal	100 % (96)	0 % (0)	N/A
Short	100 % (98)	0 % (0)	
Short-fed			
Normal	100 % (96)	0 % (0)	N/A
Short	100 % (94)	0 % (0)	
Long-fed			
Normal	100 % (40)	0 % (0)	N/A
Short	100 % (41)	0 % (0)	
TVC			
Domestic			
Normal	100 % (96)	0 % (0)	N/A
Short	100 % (98)	0 % (0)	
Short-fed			
Normal	100 % (96)	0 % (0)	N/A
Short	100 % (94)	0 % (0)	
Long-fed			
Normal	100 % (40)	0 % (0)	N/A
Short	100 % (41)	0 % (0)	

4.4 Economic Analysis of the Effect of Reducing Lairage Duration

4.4.1 Partial Budget

The economic impacts of this research were analysed in a partial budget with short duration lairage as the proposed change to the system and additional revenue calculated from any gains in HSCW as a result of reduced time in lairage. Normal duration lairage was considered as the status quo or revenue forgone. Costs saved and extra costs were included in the partial budget to account for the extra feed provided to the cattle in the short duration lairage group due to the extended feedlot exit time (cattle in short lairage being kept at the feedlot until the morning of slaughter (Day 0) as opposed to cattle in normal lairage departing feedlot on the day prior (Day -1) to slaughter), as well as the reduction in dark cutting carcasses in the domestic and short-fed export market categories.

The estimated gain in gross revenue per head by reducing time in lairage comes from the difference in HSCW between the status quo (normal duration lairage) and short duration lairage, with ration costs and penalties for dark cutting carcasses (pHu $>$ 5.7) taken into consideration. The penalty rate for dark cutting carcasses at the time of this study was \$0.60/kg, \$2.00/kg for domestic and short-fed export markets, respectively. Penalties for dark cutting carcasses were not included in the analysis for the long-fed export market group as the difference between treatment groups for the dark cutting variable was not significant.

The data presented in Table 9 indicates that the net change in gross revenue from implementing short duration lairage is \$13,649.05, \$44,952.57 and \$20,366.22 per 1,000 head for the domestic, short-fed export and long-fed export market categories, respectively.

4.4.2 Sensitivity analysis

Sensitivity analyses were conducted on the results of the partial budgets to assess a range of plausible ration quantities in kilograms, around the actual ration fed out on Day -1 ($\pm$ 20% of the ration fed out on Day -1 during the experiment, at each feedlot). It also considered a $\pm$ 1.0, 1.75 and 2.5 kg variation in HSCW for the domestic market category, and $\pm$ 4.0, 5.5 and 7.0 kg HSCW and $\pm$ 1.0, 1.7 and 2.4 kg variation in HSCW for the short-fed export and long-fed export market categories, respectively.

The sensitivity analysis revealed that the breakeven point for the ration fed out on short duration lairage Day -1 is 31.85 kg DM/hd, 102.38 kg DM/hd and 55.02 kg DM/hd for the domestic, short-fed export and long-fed export market categories, respectively (Table 10). This indicates that the benefit in gross revenue from retaining cattle at the feedlot to achieve short duration lairage is not impacted by the cost of the extra feed ration on Day -1 and is unlikely to reach the breakeven point for ration.

In contrast, a shift in the HSCW values has a greater impact on the gross revenue. The breakeven point for HSCW is 257.24 kg/hd, 369.96 kg/hd and 423.11 kg/hd for the domestic, short-fed export and long-fed export market categories, respectively. That is, the carcasses would only have to be 2.27 kg, 6.82 kg and 1.67 kg lighter for there to be no gain in gross revenue by implementing short duration lairage. However, if the difference in HSCW between normal and short duration lairage increases up to 2.5 kg, 7.0 kg and 2.4 kg for the domestic, short-fed and long-fed export market categories, respectively, the potential gains could be up to ~ \$32, \$93 and \$51 per head.

4.4.3 Benefit to industry

Table 11 estimated the benefit of implementing short duration lairage across the three market categories. The per-head gross revenue increase was \$13.65 for short-fed domestic cattle, \$44.95 for mid-fed export cattle, and \$20.37 for long-fed cattle (calculated from values in Table 9). Using a 5-year average of cattle slaughter data (*National Inventory Report*, 2023) by days on feed (DOF); 75 days

(short-fed), 138 days (mid-fed), and over 250 days (long-fed), we extrapolated the potential industry-wide benefit (Table 11). The estimated annual gain is $2,581,488 for the domestic market category. The estimated benefit for the short-fed export cattle is $26,093,475 per year; however, this is based on an average of 138 DOF where the cattle in the current study were on feed for 125 days. The estimated benefit for the long-fed export cattle was $6,865,844 per year, however, this is based on the average +250 days on feed for implementing short duration lairage, where the cattle in the current study were on feed for 340 days.

These figures represent potential annual benefits from adopting short duration lairage using assumptions of average grainfed cattle volumes per year, per DOF category (*National Inventory Report*, 2023). In addition, this extrapolation does not account for other sources of variation (see sensitivity analysis for variation in HSCW and feed consumption).

Other hard to quantify economic factors must be considered for each specific feedlot and processing facility as the net change in gross revenue from implementing short duration lairage will vary according to such factors. These factors have not been incorporated in the economic analysis because they are difficult to collect and include feedlot proximity to processing facility, trucking schedules, number of kill shifts per day, additional cost in labour (loading/unloading cattle earlier in the morning), washing cattle, antemortem inspections, and kill floor schedules. Other unquantifiable factors must also be considered, and these include animal welfare outcomes, social licence and environmental benefits which are similarly difficult to collect as pieces of data.

Table 9. Assumptions and change in gross revenue for partial budget comparing SHORT and NORMAL duration lairage (per 1,000 head)

	NORMAL	SHORT	
	Domestic Market		
Variable	**Value**		
Average lairage duration (h)	20.51	4.49	
Days on feed	74	75	
Average HSCW (kg)ǂ	256.89	259.51	
Number carcasses pHu ≤ 5.7 §	988	997	
Number carcasses pHu > 5.7 §	12	3	
Price per kg HSCW, pHu ≤ 5.7 ($/kg) *	6.01	6.01	
Price per kg HSCW, pHu > 5.7 ($/kg) *	5.41	5.41	
Ration fed Day -1 (kg/hd DM) *	5.73	11.05	
Ration cost Day -1 ($/kg) *	0.66	0.66	
Equation 1: Total feed costs/savings ($/1000 hd)	3760.78	7252.46	
Equation 2: Total value carcasses pHu ≤ 5.7 ($)	1526548.50	1556165.27	
Equation 3: Total value carcasses pHu > 5.7 ($)	16,691.47	4215.43	
Equation 4: Change in gross revenue per 1000 carcasses ($)			**13649.05**
	Short-fed Export Market		
Variable	**Value**		
Average lairage duration (h)	22.07	4.01	
Days on feed	125	126	
Average HSCW (kg)ǂ	372.14	376.78	
Number carcasses pHu ≤ 5.7 §	977	1000	
Number carcasses pHu > 5.7 §	23	0	
Price per kg HSCW, pHu ≤ 5.7 ($/kg) **	6.59	6.59	
Price per kg HSCW, pHu > 5.7 ($/kg) **	4.59	4.59	
Ration fed Day -1 (kg/hd DM) **	10.15	15.67	
Ration cost Day -1 ($/kg) **	0.52	0.52	
Equation 1: Total feed costs/savings ($/1000 hd)	5259.78	8125.47	
Equation 2: Total value carcasses pHu ≤ 5.7 ($)	2394777.56	2482224.27	
Equation 3: Total value carcasses pHu > 5.7 ($)	39628.44	0	
Equation 4: Change in gross revenue per 1000 carcasses ($)			**44952.57**
	Long-fed Export Market		
Variable	**Value**		
Average lairage duration (h)	17.53	2.14	
Days on feed	339	340	
Average HSCW (kg)ǂ	423.12	424.78	
Price per kg HSCW ($/kg) ***	12.20	12.20	
Ration fed Day -1 (kg/hd DM) ***	7.92	7.66	
Ration cost Day -1 ($/kg) ***	0.43	0.43	
Equation 1: Total feed costs/savings ($/1000 hd)	3406.41	3292.19	
Equation 2: Total value carcasses ($)	5162064.00	5182316.00	
Equation 5: Change in gross revenue per 1000 carcasses ($)			**20366.22**

DM, dry matter; hd, head of cattle; HSCW, Hot Standard Carcass Weight.

ǂ HSCW values are least squares means from statistical analysis of the impact of lairage duration on HSCW (Table 3)

§ pHu numbers are based on statistical analysis of proportion of dark cutters observed in the current trial (Table 4).

*For Domestic market category price per kg HSCW provided by collaborating processing facility and based on ESYI reports for NSW, Northwest region. Ration cost/day provided by collaborating feedlot and based on Lot Number closing reports.

**For Short-fed export market category, price per kg HSCW and ration kg and cost/day provided by collaborating processing facility and feedlot. Ration kg and cost/head/day provided as an average for all cattle for the period of the trial.

***For Long-fed export market category, price per kg HSCW, ration kg and ration cost/day provided by collaborating feedlot.

Table 10. Sensitivity analysis for rations fed on Day -1 and HSCW for short duration lairage based on results from partial budget, calculated based on 1,000 head of cattle for each market category.

SHORT Lairage Sensitivity Analysis	-2.5 kg	-1.75 kg	-1 kg	**Domestic HSCW (kg)**	+1 kg	+1.75 kg	+2.5 kg
Feed (kg/hd DM) Day -1	**257.01**	**257.76**	**258.51**	**259.51***	**260.51**	**261.26**	**262.01**
5.74	2102.18	6611.78	11121.37	17134.17	23146.96	27656.56	32166.16
7.51	940.47	5450.07	9959.67	15972.46	21985.26	26494.85	31004.45
9.28	-221.24	4288.36	8797.96	14810.75	20823.55	25333.15	29842.74
11.05**	-1382.94	3126.65	7636.25	**13649.05**	19661.84	24171.44	28681.04
12.82	-2544.65	1964.95	6474.54	12487.34	18500.14	23009.73	27519.33
				Short-fed export			
	-7.0 kg	-5.5 kg	-4.0 kg	**HSCW (kg)**	+4.0 kg	+5.5 kg	+7.0 kg
Feed (kg/hd DM) Day -1	**369.78**	**371.28**	**372.78**	**376.78***	**380.78**	**382.28**	**383.78**
11.99	747.71	10629.70	20511.69	46863.67	73215.64	83097.63	92979.62
13.83	-206.90	9675.09	19557.08	45909.05	72261.03	82143.02	92025.01
15.67**	-1161.52	8720.48	18602.47	**44954.44**	71306.42	81188.41	91070.40
17.51	-2116.13	7765.86	17647.85	43999.83	70351.80	80233.79	90115.78
19.35	-3070.74	6811.25	16693.24	43045.21	69397.19	79279.18	89161.17
				Long-fed export			
	-2.4 kg	-1.7 kg	-1 kg	**HSCW (kg)**	+1 kg	+1.7 kg	+2.4 kg
Feed (kg/hd DM) Day -1	**422.38**	**423.08**	**423.78**	**424.78***	**425.78**	**426.48**	**427.18**
4.12	-7391.58	1148.42	9688.42	21888.42	34088.42	42628.42	51168.42
5.89	-8152.68	387.32	8927.32	21127.32	33327.32	41867.32	50407.32
7.66**	-8913.78	-373.78	8166.22	**20366.22**	32566.22	41106.22	49646.22
9.43	-9674.88	-1134.88	7405.12	19605.12	31805.12	40345.12	48885.12
11.20	-10435.98	-1895.98	6644.02	18844.02	31044.02	39584.02	48124.02

*HSCW achieved by cattle in the SHORT lairage group, values in columns to either side represent losses or gains in carcass weight and the associated additional gross revenue.

**Feed delivered to cattle on Day -1 in the SHORT lairage group, values in rows above and below represent losses or gains in gross revenue associated with increased or decreased ration delivered.

Table 11. Estimated benefit to the industry of adopting short duration lairage, based on three market categories. Adapted from (*National Inventory Report*, 2023).

	Domestic (75 DOF)	**Export mid-fed (150 DOF)**	**Export long-fed (+250 DOF)***
Days on feed from project	75	125	340
Head killed, 5-year average*	189,120	580,500	348,520
Gross revenue from short duration lairage ($/hd)**	13.65	44.95	20.37
Total benefit per year for DOF for industry	$2,581,488	$26,093,475	$6,865,844

*Number of head killed over a 5-year average (2019-2023) from the National Inventory Report. Note: Long-fed export category is all cattle fed over 250 DOF which is not a true representation of the findings from the current project in which cattle were on feed for an average of 340 days.

**Gross revenue ($/hd) calculated from partial budget in Table 9.

5. Conclusion

5.1 Discussion

Lairage duration in Australia has historically been overnight with long lairage durations of greater than 16 hours for feedlot cattle (Ferguson et al., 2007). Long lairage periods, even though the cattle have access to water, can lead to cellular dehydration, increased exposure to stress and increased incidences of dark cutting (Clariget et al., 2021). This leads to reduced carcass weights and higher incidences of grid price deductions due to carcasses not meeting MSA requirements, for example, dark cutters (pH > 5.70) (Ferguson & Warner, 2008). Short duration lairage is the practice of reducing the time in lairage from normal lairage (12 to 24 hours) to short lairage (2 to 4 hours). By limiting time in lairage and time off feed, cattle remain hydrated with greater liver glycogen supplies maintaining blood glucose, optimising muscle glycogen status and carcass weight (Ferguson et al., 2007). Short duration lairage can help reduce stress, improves animal welfare and production responses as seen by the results of this experiment and in past MLA research (B.FLT.4002, B.FLT.4017).

Reducing time in lairage from ~ 21.5 hours down to ~ 4.5 hours resulted in 2.62 kg, 4.64 kg and 1.66 kg heavier HSCW in the domestic, short-fed export and long-fed export cattle, respectively. Similar results were observed with cold carcass weight, with heavier carcasses of 2.39 kg and 4.78 kg for the short lairage groups compared with normal lairage groups for the domestic and short-fed export cattle, respectively. These findings could be due to increased cellular hydration in the cattle exposed to shorter lairage times compared with cattle exposed to longer lairage times, however the true mechanism causing the differences was not evaluated as a part of this experiment. Cattle in the short lairage groups were kept in their feedlot pens with access to feed and water until exit, resulting in a decreased time for this group when they were off feed. For example, cattle in the domestic market category short lairage group were off feed for ~ 6.12 hours prior to stunning (4.49 hours in lairage) compared with cattle in the normal lairage group which were off feed for ~ 22.06 hours (20.51 hours in lairage) prior to stunning. For cattle in the short-fed export market category short lairage group, time off feed prior to stunning was ~ 7.21 hours (4.01 hours in lairage) compared with ~ 24.57 hours (22.07 hours in lairage) for the normal lairage group. For the cattle in the long-fed export market category short lairage group, time off feed prior to stunning was ~ 5.52 hours (2.14 hours in lairage) compared with ~ 21.35 hours (17.53 hours in lairage) for the normal lairage group. Furthermore, while water is offered to cattle in lairage, not all cattle will drink, or they may not drink sufficiently to rehydrate. In addition, cattle exposed to a novel environment which elicits fear behaviours or a preference to “explore” rather than drink (del Campo Gigena et al., 2021; Ferguson & Warner, 2008; Tadich et al., 2005). Cattle exposed to longer lairage durations as in the current study, may not drink sufficient water to rehydrate which may contribute to the lighter carcass weights as observed in all three export market categories. The higher muscle cell hydration may also explain the reason for the results in HSCW to carry through to the cold carcass weights. These findings correspond with those reported in the two MLA projects (B.FLT.4017 and B.FLT.4002), as well as Clariget et al. (2021) who found that a shorter fasting and lairage duration gave a 3.68 kg advantage over cattle in lairage for 14 hours, indicating that reducing lairage duration may allow cattle to retain liveweight and subsequently hot and cold carcass weights.

When ruminants encounter stressful situations, the sympatho-adrenomedullary (SAM) system and hypothalamic-pituitary-adrenal (HPA) axis are activated and cattle tend to stop eating, drinking and ruminating (Schirmann et al., 2011), which could influence normal energy metabolism, production of protein and levels of glycogen in the muscle. The production of cortisol is triggered by the activation of the HPA and promotes the breakdown of protein within the muscle (Niu et al., 2022). In lairage, cattle are exposed to new environments and sounds as well as increased handling by unfamiliar personnel, which can lead to increased levels of cortisol for up to 15 hours (del Campo Gigena et al.,

2021). Adrenaline, a hormone released when the SAM system is activated (Kaiser & Jaillardon, 2023), has been shown to influence the levels of glycogen in the liver (Carroll & Forsberg, 2007) and muscle (Gardner et al., 2014; Tarrant, 1989). Changes in muscle glycogen may influence overall carcass weight through the association between glycogen and water molecules within the muscle contributing to muscle weight (Fernández-Elías et al., 2015; Shiose et al., 2016). Along with stress-reduced rumination, reduced protein turnover and the production of cortisol and adrenaline, extended periods of time off feed may also contribute to muscle glycogen decline, influencing meat quality and carcass weight (Moss, 1992; Pethick et al., 1995). Without feed, ruminant gut microbes cannot produce the amino acids needed for muscle production (Storm & Ørskov, 1983). Similarly, without feed, the production of propionate is limited which reduces glucose produced via gluconeogenesis, resulting in less muscle glycogen via glycogenesis (Warriss et al., 1987). Additionally, cattle may use up stores of this energy, reducing muscle glycogen levels and overall carcass weight. A recent study found that HSCW and liver glycogen levels decreased as duration of feed withdrawal increased from 24, 28, 32 up to 36 hours (B.FLT.5009). Cattle in the normal lairage group of the current study were off feed for maximum 27.5 hours indicating a potential for glycogen mobilisation that may have impacted muscle weight.

Short lairage duration during winter conditions did not impact microbiological contamination of hides or carcasses, particularly in relation to the government performance criteria and 'ALERT' thresholds (Department of Agriculture, 2023). *Salmonella* spp. was detected on five of the 465 hides sampled but was not detected on any of the corresponding carcasses. *E. coli* was detected on most hides and carcasses but the counts were well below the Department of Agriculture (2023) threshold (refer to Table 1). These results are similar to those reported by (B.FLT.4017) who found no difference between lairage treatments for microbiological status, although that study was conducted through summer conditions. The industry concern was that the reduced time in lairage would lead to reduced time for washing cattle which would increase the risk of carcass contamination. The lack of difference between treatment groups in the current study could be due to a number of factors including; a short wash is sufficient or washing doesn't remove microbes, short lairage group of cattle spend less time in lairage pens with less time for cattle to cattle, and cattle to infrastructure cross-contamination or the cuts made on the kill floor and hide removal processors is done to a high standard and microbes are not being transferred onto carcass at the hide puller (Small et al., 2002). Studies have shown that often there are a few cattle in a group that are 'high shedders' of microbes and these are the cattle that spread the microbes to the rest of the group (Mechie et al., 1997; Robinson et al., 2004). However, this was not observed in the current study across any of the market categories. Therefore, the less time cattle spend in close contact with these high shedders, the less cross-contamination there will be.

In the current study, ultimate pH levels were not impacted by lairage duration, but the incidence of dark cutting carcasses was reduced in the SHORT lairage groups from the domestic and short-fed export market categories. Cattle in SHORT lairage had 0.3% and 0% dark cutters compared with 1.2% and 2.23% dark cutters in the NORMAL lairage groups of the domestic and short-fed export market categories, respectively. These values sit below the national industry average for pH non-compliance which, in 2023-2024, was 4.4% (MLA, 2024). It should also be noted, that in the short-fed export market category, 15 of the 22 dark cutting carcasses occurred in one of the 16 replicates. Similarly, meat colour was darker for the domestic and short-fed export market category cattle exposed to the longer duration lairage. A previous report also observed increased meat colour for cattle exposed to longer lairage periods, although in that study there was a clear link between muscle pH increases and meat colour increases (B.FLT.4002). Ossification and fat colour also appeared to have been affected by lairage duration in the current study with greater ossification and lower fat colour for the short duration lairage group of the short-fed export category. However, ossification occurs over long timeframes (Bonny et al., 2016) and fat colour is produced by varied diets (Yang et al., 1992). Therefore, it is unlikely that these differences observed are biologically related to lairage duration,

indicating the differences may be due to random variation or MSA grader bias between treatment groups. Changes in EMA were also observed for the short-fed export category cattle dependent on lairage duration. This may be associated with the possible reduction in muscle glycogen and associated water molecules from cattle exposed to longer duration, reducing muscle weight and size. Overall, carcass grading characteristics were not negatively affected by lairage duration which is positive for industry.

The cost benefit analysis undertaken in this study has shown that some economic gains can be made by shifting from normal duration lairage to short duration lairage, due to the increases in HSCW and reduction in dark cutting observed in the short duration lairage carcasses. For each market category the cost of the additional ration fed out on short duration lairage Day -1 was outweighed by the HSCW yield gain recorded. The sensitivity results revealed that a small decrease of 2.27 kg or 1.67 kg in the short duration lairage HSCW would result in no economic benefit gained from making the lairage change in the domestic and long-fed export market categories. The breakeven HSCW yield of 6.82 kg per head for the short-fed export market category is a larger buffer, indicating a less volatile net gain relative to the other market categories. The small gains in average HSCW underpinning the net gain across all three market categories should be used with caution as the variation in site-specific operating costs will affect the outcome.

This study did not include other operating costs that will have a small, but measurable impact on the change in estimated. These include wage and wage related costs, machinery costs and electricity costs. Scaling the partial budget results up to site or industry levels could lead to an overstatement of economic gains due to the omission of these operational costs. Individual sites should consider their own management practices and account for any additional costs incurred to implement the change. A separate assessment of the cashflow implications should also be undertaken. Given the small loss in HSCW required to breakeven, future work should account for the myriad of operational cost changes required on Day -1 to adopt short duration lairage to fully understand the financial implications of the change at scale.

Notwithstanding the tight HSCW parameters required to achieve an economic gain from adopting short duration lairage, other factors should also be taken into consideration. Benefits from other non-monetary factors, such as improvements in welfare from reduced exposure to novel environments, may have a greater impact on the decision to adopt the practice. As previously stated, the incidence of dark cutting was reduced in the SHORT lairage groups from the domestic and short-fed export market categories which could have both positive welfare and economic impacts.

Previous MLA research on grainfed domestic heifers (B.FLT.4002) and mid-fed export cattle (B.FLT.4017) have reported carcass weight benefits of 3.0 to 3.9 kg; and 6.2 to 7.4kg, respectively during summer. Furthermore, MLA project B.FLT.4017 reported higher liver glycogen levels in short lairage duration cattle, indicating improved animal welfare, while project B.FLT.4002, to reduce dark cutting, recommended lairage should not exceed 3 hours for British-type heifers. In addition, project B.FLT.4017 indicated a potential economic benefit to the industry of $35/head by reducing lairage time. Microbiological contamination is seen as one of the barriers to adoption for short duration lairage (Dewell et al., 2008) but project B.FLT.4017 found there were no differences in microbiological status of carcasses for these cattle either. Therefore, combining the results from previous MLA studies and the current finding from three market categories during winter conditions, indicate reducing time off feed and time in lairage has positive carcass weight gain benefits, as well as economic benefits, carcasses are food safe and short duration lairage has positive welfare outcomes for cattle consigned to slaughter.

5.2 Key findings

This study contributes to the body of evidence that short duration lairage provides a benefit to the red meat industry, and that it is possible to implement a proportion of a daily kill schedule to same day delivery and processing of cattle across a range of market categories throughout winter without compromising food safety.

- HSCW, CCW and dressing percentage were higher for cattle exposed to shorter lairage durations compared with the normal lairage duration.
- Incidences of dark cutting were reduced when cattle were exposed to shorter lairage durations compared with the normal lairage duration.
- Microbiological status of carcasses was within industry food safety standards even during winter conditions.

5.3 Benefits to industry

The results from this study could lead to a huge impact on the red meat supply chain.

- HSCW was 2.62 kg, 4.64 kg and 1.66 kg heavier when cattle were exposed to short duration lairage for domestic, short-fed export and long-fed export market categories, respectively.
- Reducing time in lairage also decreases the incidences of dark cutting which is a huge economic cost to the industry.
- Economic analysis, which accounted for ration costs, revealed a $13.65, $44.95 and $20.37 per head net increase in gross revenue from implementing short duration lairage in the domestic, short-fed export and long-fed export market categories, respectively.

6. Future research and recommendations

Recommendations:

- Short duration lairage can be adopted to a proportion of a daily kill schedule, but this takes organisation and scheduling of the kill in relation to the distance that needs to be travelled by each mob along with ante-mortem inspection and washing needs.
- Time spent in stress-inducing environments should be reduced for all feedlot cattle.
- Where possible, any reduction in time off feed and time in lairage is beneficial
- Share research findings to ALFA members, industry and government veterinarians and other processing facilities beyond those involved in the current project.

Future research:

- Should include extended economic analysis accounting for additional labour, trucking schedules and other factors such as reduction in dark cutting carcasses.
- Investigate the effects of lairage duration on grass fed cattle and sheep.
- Review current curfew and trucking guidelines for sheep and cattle.
- Review current washing protocols at processing facilities with the aim to minimise the number of times cattle are wet and the duration of time they undergo washing ante-mortem.
- Research should continue on ways to clean the cutting lines on the hides of cattle post-mortem to assist with the desire to minimise washing ante-mortem and maintain a very clean carcass.

7. References

Antic, D., Blagojevic, B., Ducic, M., Nastasijevic, I., Mitrovic, R., & Buncic, S. (2010). Distribution of microflora on cattle hides and its transmission to meat via direct contact [Article]. *Food Control*, *21*(7), 1025-1029. https://doi.org/10.1016/j.foodcont.2009.12.022

Antic, D., Houf, K., Michalopoulou, E., & Blagojevic, B. (2021). Beef abattoir interventions in a risk-based meat safety assurance system [Review]. *Meat Science*, *182*, 108622. https://doi.org/10.1016/j.meatsci.2021.108622

Arias, R. A., & Mader, T. L. (2011). Environmental factors affecting daily water intake on cattle finished in feedlots. *Journal of Animal Science*, *89*(1), 245-251. https://doi.org/10.2527/jas.2010-3014

AAWCS. (2024). Industry Animal Welfare Standards - Fourth Edition. In *Industry animal welfare standards for livestock processing establishments preparing meat for human consumption*. (AMIC). Crows Nest, New South Wales, Australia.

Bach, S. J., McAllister, T. A., Mears, G. J., & Schwartzkopf-Genswein, K. S. (2004). Long-haul transport and lack of preconditioning increases fecal shedding of Escherichia coli and Escherichia coli O157:H7 by calves† [Article]. *Journal of food protection*, *67*(4), 672-678. https://doi.org/10.4315/0362-028X-67.4.672

Barham, A. R., Barham, B. L., Johnson, A. K., Allen, D. M., Blanton, J. R., & Miller, M. F. (2002). Effects of the transportation of beef cattle from the feedyard to the packing plant on prevalence levels of Escherichia coli O157 and Salmonella spp [Article]. *Journal of food protection*, *65*(2), 280-283. https://doi.org/10.4315/0362-028X-65.2.280

Bonny, S. P. F., Pethick, D. W., Legrand, I., Wierzbicki, J., Allen, P., Farmer, L. J., Polkinghorne, R. J., Hocquette, J. F., & Gardner, G. E. (2016). Ossification score is a better indicator of maturity related changes in eating quality than animal age. *animal*, *10*(4), 718-728. https://doi.org/10.1017/S1751731115002700

Carroll, J. A., & Forsberg, N. E. (2007). Influence of Stress and Nutrition on Cattle Immunity [Review]. *Veterinary Clinics of North America: Food Animal Practice*, *23*(1), 105-149. https://doi.org/10.1016/j.cvfa.2007.01.003

Clariget, J., Banchero, G., Luzardo, S., Fernández, E., Pérez, E., La Manna, A., Saravia, A., del Campo, M., Ferrés, A., & Canozzi, M. E. A. (2021). Effect of pre-slaughter fasting duration on physiology, carcass and meat quality in beef cattle finished on pastures or feedlot. *Research In Veterinary Science*, *136*, 158-165. https://doi.org/10.1016/j.rvsc.2021.02.018

Collis, V. J., Reid, C. A., Hutchison, M. L., Davies, M. H., Wheeler, K. P. A., Small, A., & Buncic, S. (2004). Spread of marker bacteria from the hides of cattle in a simulated livestock market and at an abattoir [Article]. *Journal of food protection*, *67*(11), 2397-2402. https://doi.org/10.4315/0362-028X-67.11.2397

del Campo Gigena, M., Soares de Lima, J. M., Brito, G., Manteca, X., Hernández, P., & Montossi, F. (2021). Effect of finishing diet and lairage time on steers welfare in Uruguay. *Animals*, *11*(5), 1329. https://doi.org/10.3390/ani11051329

Department of Agriculture, F. a. F. (2023). *Microbiological manual for sampling and testing of export meat and meat products*. Online only: Department of Agriculture, Fisheries and Forestry Retrieved from https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/aqis/exporting/

meat/elmer3/index/methods-microbiological-test-meat/manual-microbiological-programs.pdf

Dewell, G. A., Simpson, C. A., Dewell, R. D., Hyatt, D. R., Belk, K. E., Scanga, J. A., Morley, P. S., Grandin, T., Smith, G. C., Dargatz, D. A., Wagner, B. A., & Salman, M. D. (2008). Impact of transportation and lairage on hide contamination with Escherichia coli O157 in finished beef cattle. *Journal of food protection*, *71*(6), 1114-1118. https://doi.org/10.4315/0362-028x-71.6.1114

Díaz, M. T., Vieira, C., Pérez, C., Lauzurica, S., de Chávarri, E. G., Sánchez, M., & De la Fuente, J. (2014). Effect of lairage time (0h, 3h, 6h or 12h) on glycogen content and meat quality parameters in suckling lambs [Article]. *Meat Science*, *96*(2, Part A), 653-660. https://doi.org/10.1016/j.meatsci.2013.10.013

Ferguson, D. M., & Gerrard, D. E. (2014). Regulation of post-mortem glycolysis in ruminant muscle. *Animal Production Science*, *54*(4), 464-481. https://doi.org/10.1071/AN13088

Ferguson, D. M., Shaw, F. D., & Stark, J. L. (2007). Effect of reduced lairage duration on beef quality [Article]. *Australian journal of experimental agriculture*, *47*(7), 770-773. https://doi.org/10.1071/EA05212

Ferguson, D. M., & Warner, R. D. (2008). Have we underestimated the impact of pre-slaughter stress on meat quality in ruminants? [Review]. *Meat Science*, *80*(1), 12-19. https://doi.org/10.1016/j.meatsci.2008.05.004

Fernández-Elías, V. E., Ortega, J. F., Nelson, R. K., & Mora-Rodriguez, R. (2015). Relationship between muscle water and glycogen recovery after prolonged exercise in the heat in humans. *European Journal of Applied Physiology*, *115*(9), 1919-1926. https://doi.org/10.1007/s00421-015-3175-z

Gardner, G. E., McGilchrist, P., & Pethick, D. W. (2014). Ruminant glycogen metabolism. *Animal Production Science*, *54*(10), 1575-1583. https://doi.org/10.1071/AN14434

Immonen, K., Ruusunen, M., Hissa, K., & Puolanne, E. (2000). Bovine muscle glycogen concentration in relation to finishing diet, slaughter and ultimate pH. *Meat Science*, *55*(1), 25-31. https://doi.org/10.1016/S0309-1740(99)00121-7

Jones, S. D. M., Schaefer, A. L., Robertson, W. M., & Vincent, B. C. (1990). The effects of withholding feed and water on carcass shrinkage and meat quality in beef cattle. *Meat Science*, *28*(2), 131-139. https://doi.org/10.1016/0309-1740(90)90037-7

Kaiser, M., & Jaillardon, L. (2023). Pathogenesis of the crosstalk between reproductive function and stress in animals—part 1: Hypothalamo–pituitary–adrenal axis, sympatho-adrenomedullary system and kisspeptin. *Reproduction in Domestic Animals*, *58*(S2), 176-183. https://doi.org/10.1111/rda.14444

Lammers, G. A. C., McConnel, C. S., Jordan, D., Ayton, M. S., Morris, S., Patterson, E. I., Ward, M. P., & Heller, J. (2015). Synchronization of E. coli O157 shedding in a grass-fed beef herd: a longitudinal study [Article]. *Epidemiology and Infection*, *143*(15), 3244-3255. https://doi.org/10.1017/S0950268815000588

Loudon, K. M. W., Tarr, G., Lean, I. J., Polkinghorne, R., McGilchrist, P., Dunshea, F. R., Gardner, G. E., & Pethick, D. W. (2019). The impact of pre-slaughter stress on beef eating quality. *Animals (Basel)*, *9*(9). https://doi.org/10.3390/ani9090612

Mechie, S. C., Chapman, P. A., & Siddons, C. A. (1997). A fifteen month study of Escherichia coli O157:H7 in a dairy herd. *Epidemiol Infect*, *118*(1), 17-25. https://doi.org/10.1017/s0950268896007194

MLA. (2024). *MSA Annual outcomes report 2023-2024*. M. L. Australia. https://www.mla.com.au/globalassets/mla-corporate/marketing-beef-and-lamb/documents/meat-standards-australia/mla-msa-annual-outcomes-report-2324-web.pdf

Moss, B. W. (1992). Lean meat, animal welfare and meat quality. In D. E. Johnston, M. K. Knight, & D. A. Ledward (Eds.), *The chemistry of muscle-based foods* (Vol. 106, pp. 62-76). The Royal Society of Chemistry.

National Inventory Report. (2023).

Niu, X., Ding, Y., Chen, S., Gooneratne, R., & Ju, X. (2022). Effect of immune stress on growth performance and immune functions of livestock: Mechanisms and prevention. *Animals*, *12*(7), 909. https://doi.org/10.3390/ani12070909

Park, B. Y., Hwang, I. H., Cho, S. H., Yoo, Y. M., Kim, J. H., Lee, J. M., Polkinghorne, R., & Thompson, J. M. (2008). Effect of carcass suspension and cooking method on the palatability of three beef muscles as assessed by Korean and Australian consumers. *Australian journal of experimental agriculture*, *48*(11), 1396-1404. https://doi.org/10.1071/EA07189

Pethick, D. W., Rowe, J. B., & Tudor, G. (1995). Glycogen metabolism and meat quality. Recent advances in animal nutrition in Australia, Armidale, NSW, Australia.

Robinson, S. E., Wright, E. J., Hart, C. A., Bennett, M., & French, N. P. (2004). Intermittent and persistent shedding of Escherichia coli O157 in cohorts of naturally infected calves. *Journal of Applied Microbiology*, *97*(5), 1045-1053. https://doi.org/10.1111/j.1365-2672.2004.02390.x

Schirmann, K., Chapinal, N., Weary, D. M., Heuwieser, W., & von Keyserlingk, M. A. G. (2011). Short-term effects of regrouping on behavior of prepartum dairy cows. *Journal of Dairy Science*, *94*(5), 2312-2319. https://doi.org/10.3168/jds.2010-3639

Shiose, K., Yamada, Y., Motonaga, K., Sagayama, H., Higaki, Y., Tanaka, H., & Takahashi, H. (2016). Segmental extracellular and intracellular water distribution and muscle glycogen after 72-h carbohydrate loading using spectroscopic techniques. *Journal of Applied Physiology*, *121*(1), 205-211. https://doi.org/10.1152/japplphysiol.00126.2016

Small, A., & Buncic, S. (2009). Potential for the cross-contamination of the hides of cattle while they are held in lairage [Article]. *Veterinary Record*, *164*(9), 260-265. https://doi.org/10.1136/vr.164.9.260

Small, A., Reid, C. A., Avery, S. M., Karabasil, N., Crowley, C., & Buncic, S. (2002). Potential for the spread of Escherichia coli O157, Salmonella, and Campylobacter in the lairage environment at abattoirs [Article]. *Journal of food protection*, *65*(6), 931-936. https://doi.org/10.4315/0362-028x-65.6.931

Stewart, S. M., Polkinghorne, R., Pethick, D. W., & Pannier, L. (2024). Carcass assessment and value in the Australian beef and sheepmeat industry [Review]. *Animal Frontiers*, *14*(2), 5-14. https://doi.org/10.1093/af/vfae005

Storm, E., & Ørskov, E. R. (1983). The nutritive value of rumen micro-organisms in ruminants: 1. Large-scale isolation and chemical composition of rumen micro-organisms [Article]. *British Journal of Nutrition*, *50*(2), 463-470. https://doi.org/10.1079/BJN19830114

Tadich, N., Gallo, C., Bustamante, H., Schwerter, M., & van Schaik, G. (2005). Effects of transport and lairage time on some blood constituents of Friesian-cross steers in Chile. *Livestock Production Science*, *93*(3), 223-233. https://doi.org/10.1016/j.livprodsci.2004.10.004

Tarrant, P. V. (1989). Animal behaviour and environment in the dark-cutting condition in beef - A review. *Irish Journal of Food Science and Technology*, *13*(1), 1-21. http://www.jstor.org/stable/25580937

Thompson, J. M. (2004). The effects of marbling on flavour and juiciness scores of cooked beef, after adjusting to a constant tenderness. *Australian journal of experimental agriculture*, *44*(7), 645-652. https://doi.org/10.1071/EA02171

Warriss, P. D., Brown, S. N., Bevis, E. A., Kestin, S. C., & Young, C. S. (1987). Influence of food withdrawal at various times preslaughter on carcass yield and meat quality in sheep. *Journal of the Science of Food and Agriculture*, *39*(4), 325-334. https://doi.org/10.1002/jsfa.2740390407

Williams, K. J., Ward, M. P., Dhungyel, O. P., & Hall, E. J. S. (2015). Risk factors for Escherichia coli O157 shedding and super-shedding by dairy heifers at pasture [Article]. *Epidemiology and Infection*, *143*(5), 1004-1015. https://doi.org/10.1017/S0950268814001630

Yang, A., Larsen, T. W., & Tume, R. K. (1992). Carotenoid and retinol concentrations in serum, adipose tissue and liver and carotenoid transport in sheep, goats and cattle. *Australian Journal of Agricultural Research*, *43*(8), 1809-1817. https://doi.org/10.1071/AR9921809