Quality of lamb meat from the Information Nucleus Flock


ACooperative Research Centre for Sheep Industry Innovation, Armidale, NSW 2351, Australia.
BLivestock Production Sciences, Department of Primary Industries, 600 Sneydes Road, Vic. 3030, Australia.
CDepartment of Agriculture and Food WA, Baron Hay Court, South Perth, WA 6151, Australia.
DSARDI Livestock Systems, Struan Research Centre, PO Box 613, Naracoorte, SA 5271, Australia.
EBiosciences Research Division, Department of Primary Industries, LaTrobe University, Bundoora, Vic. 3075, Australia.
FSchool of Veterinary & Biomedical Sciences, Murdoch University, 90 South Street, Murdoch, WA 6150, Australia.
GSchool of Rural and Environmental Science, University of New England, Armidale, NSW 2351, Australia.
H36 Paynes Road, Hamilton, Vic. 3300, Australia.
ICSIRO Division of Livestock Industries, Queensland Bioscience Precinct, 306 Carmody Road, St Lucia, Qld 4067, Australia.
Industry & Investment NSW, Centre for Red Meat and Sheep Development, Cowra, NSW 2794, Australia.
KPresent address: CSIRO Food and Nutritional Sciences, Private Bag 16, Werribee, Vic. 3030, Australia.
ILCorresponding author. Email: robyn.warner@csiro.au

Abstract. The effects of production and processing factors on tenderness, and colour of lamb meat produced from 7 locations as part of the Australian Sheep Industry CRC’s Information Nucleus flock were investigated, using data from 2052 lambs slaughtered in 2007. At 24 h post-slaughter, samples of m. longissimus lumborum (LL) and m. semimembranosus (SM) were collected for measurement of intramuscular fat (IMF), myoglobin, iron and copper and fresh meat colour (L*, a*, b*) and pH at 24 h measured on the LL. pH and temperature measurements made pre-rigor were used to calculate the pH at 18°C. Tenderness was measured by LL shear force at days 1 (SF1) and 5 (SF5) post-slaughter, the shear force difference (SF-diff) and SM compression and collagen concentration were determined. Retail colour stability was assessed using over-wrapped LL under simulated retail display for 3 days, according to the change in the oxymyoglobin/metmyoglobin ratio. All traits were affected by flock and date of slaughter (P < 0.001). After 4 days of ageing, 70–95% of the LL samples from all flocks, except for one, had acceptable tenderness for consumers based on their shear force. Low IMF, high LL pH at 18°C and high pH at 24 h increased SF1 and SF5 and also had an effect on SF-diff (P < 0.001). The retail colour of 44.8% of the samples on day 3 of retail display were lower than acceptable. Retail colour was influenced by IMF, pH18 and the concentration of iron and copper (P < 0.001). In conclusion, breeding and management practices that increase muscle IMF levels and reduce ultimate pH values and processing practices that result in moderate rates of pH fall post-slaughter, improve the tenderness of lamb. Extension of retail colour stability may be antagonistic to traits associated with tenderness and nutritional traits, particularly IMF and mineral levels.

Introduction

Consumers expect premium quality as well as value from lamb meat (Pethick et al. 2006), both of which are influenced by environmental and genetic factors. Hughes (2008) recently showed that 41% of consumers in the EU are prepared to pay more for high quality food. Furthermore, consumers of beef have been reported to be prepared to pay as much as two to three times more for quality (Lyford et al. 2010). To satisfy the demands of an increasingly discerning consumer, who will demand and pay for quality, it is vital that the lamb industry understands the key control points for quality and how they can be managed. The Information Nucleus Flock provides a unique opportunity for examination of non-genetic factors influencing lamb quality, across a range of environments.

The plane of nutrition, growth rate of an animal and feeding regime during the finishing phase have been variously shown to
influence carcass and product quality (Warner et al. 2010). For example, feeding animals at a low plane of nutrition may result in tough meat (high shear force) in lamb meat (Hopkins et al. 2005b) and low consumer sensory scores for beef (Fishell et al. 1985). Several biochemical and biophysical mechanisms may explain the relationship between animal nutrition and meat eating quality. Slow growth may decrease levels of proteases (Harper 1999) and increase the fasicular width of connective tissue in muscle (Allingham et al. 2009), both of which would increase meat toughness. High nutrition levels in the 1999) and increase the fascicular width of connective tissue in beef cattle (Reverter et al. 2003) and it is postulated that this may also be the case for sheep.

Genetic factors also influence meat eating quality. Various studies have found that breed affects the tenderness of lamb meat (Sanudo et al. 2003). More importantly, genetic selection for increased muscle development has been associated with reduced tenderness in lamb meat (Hegarty et al. 2006). Increased myofibrillar toughness, as measured by shear force (Hopkins and Fogarty 1998; Hopkins et al. 2007a), reduced consumer palatability (Hopkins et al. 2005b) and increased connective tissue, as measured by compression (Allingham et al. 2006), have all been associated with selection for muscling.

Selection for growth or muscling generally has small effects on the colour of lamb meat (Hopkins et al. 2005b, 2007a). However, meat colour does vary between different strains of Merinos (Hopkins et al. 2005a), possibly due to this breed’s susceptibility to dark cutting, which is caused by a high ultimate pH (pHu) (Gardner et al. 1999; Warner et al. 2007b). If the pH of Merino meat can be managed to remain low, the colour of the loin can be comparable to other breeds of sheep (Warner et al. 2007b). Meat becomes darker and redder as lamb age increases (Warner et al. 2007a), but meat colour can also be influenced by nutrition (Hopkins et al. 2007b).

Progeny from the same sires have been produced at the eight sites of the Australian Sheep Industry Cooperative Research Centre’s Information Nucleus Flock (INF). As these sites are distributed across Australia, this represents an unprecedented opportunity to investigate non-genetic effects on meat quality independently of genetic effects. Herein we present recent results from the 2007 cohort of INF lambs on the influence of production and processing factors on lamb meat shear force, fresh colour and colour stability during display.

Materials and methods
The design of the INF was outlined by Fogarty et al. (2007). The results presented in this paper are based on data from the first year’s progeny (2007) of this 5-year program. In 2007, 2052 lambs were produced for slaughter at seven research sites across Australia (Katanning WA, Cowra NSW, Kirby NSW, Struan SA, Turretfield SA, Hamilton Vic., and Rutherglen Vic.), which represent a broad cross-section of Australian production environments. An eighth research site was introduced after 2007, at Trangie, NSW (labelled Flock 2). The lambs were the progeny of Merino and crossbred ewes that were artificially inseminated to 94 performance-measured sires representing the major production types in the Australian sheep industry. Lambs were finished under several different systems and slaughtered between 5 and 14 months of age, over several kill dates at each site in order to reach the target carcass weight of ~21 kg. The pre-slaughter feeding regimes for each slaughter date and flock are described in Ponnampalam et al. (2010). All lambs were yared the day before slaughter, weighed after a 6 h feed and water curfew, transported to abattoir lairage and slaughtered the following day. Lambs were slaughtered at five different abattoirs. All carcasses were electrically stimulated post-dressing and were trimmed according to AUS-MEAT specifications (Anon. 1998). A description of the electrical stimulation system at each abattoir is provided by Pearce et al. (2010). Carcasses were measured and sampled for a wide range of carcass and meat quality traits after they were chilled overnight at 0–2°C.

Sampling and measurements
The pH and temperature of the m. longissimus lumborum (LL) of each carcass was measured 4 times post-slaughter as described by Pearce et al. (2010). The rate of decline in pH and temperature during the first 24 h post-mortem is defined by; (1) the pH of the LL when the LL reached 18°C (pH18), and (2) the temperature of the carcass when the carcass reaches pH6 (pH6TEMP). These values were calculated as described by Pearce et al. (2010). The pH of the LL at 24 h post-mortem (pH24 LL) was measured using the same equipment as used for the rate of pH decline.

Approximately 24 h after slaughter, the eye of shortloin (LL) was removed from both sides of the carcass and the subcutaneous fat and epimysium (silver skin) were removed. The topside, cap off (m. semimembranosus, SM), was removed from one hindleg. A 65 g sample of the SM was vacuum packed and frozen at −20°C on day 1 post-slaughter and subsequently analysed for compression. Two 40 g diced samples of the LL were collected for mineral, myoglobin and intramuscular fat analysis. Samples were frozen one day post-mortem at −20°C and for mineral and intramuscular fat analysis, were subsequently commercially freeze-dried. A 4 g sample of the SM was placed in a 5 ml tube, frozen at −20°C on day 1 post-slaughter and subsequently analysed for total collagen content and intramuscular fat, after freeze drying. Freeze drying was conducted using a commercial freeze-drier (Cuddon FD 1015; Cuddon Freeze Dry, Blenheim, NZ). A 5 cm portion of loin was cut from the cranial end of one of the short loins, packed in a vacuum-sealed gas-impermeable plastic bag and stored at 4°C for subsequent retail colour measurement. Two 65 g samples were taken from the LL for shear force measurement, one from the middle of the LL and one towards the cranial end. The cranial and middle samples were used to measure shear force on days 1 and 5 post slaughter. Each sample was vacuum packed and
frozen at \(-20^\circ C\), immediately in the case of the day 1 sample (SF1) and after storage at \(2 \text{--} 4^\circ C\) for 4 days for the day 5 sample (SF5). Shear force samples from flocks 1, 3 and 8 were analysed by the DPI-Cowra laboratory and compression samples from the same flocks were analysed by the DAFWA laboratory. Shear force samples from flocks 4, 5, 6 and 7 were analysed by the DPI-Werribee laboratory and compression samples from the same flocks were analysed by the SARDI laboratory.

**Fresh meat colour**

Fresh meat colour was measured 19–24 h after slaughter (one day post-slaughter) using a Minolta chromameter, D65 illuminant with a 2° standard observer and 8 mm aperture. The chromameter was calibrated on a white tile before measurements and the values recorded were \(L^*\) (lightness), \(a^*\) (redness) and \(b^*\) (yellowness). Prior to measurement, each carcass was cut at the 12th rib through the LL and the cut surface was exposed to air for 30–40 min at 2–4°C. Measurements were made in triplicate and the mean was used for analysis.

**Shear force, compression and collagen**

The sample preparation and cooking method for shear force and compression was based on the method published by Hopkins and Thompson (2001) for lamb.

**Cooking**

For measurement of shear force and compression, a water bath was pre-heated to 71°C and samples were taken directly from the freezer and placed in the water-bath and cooked for 35 min. Samples from several flocks were included in each cooking batch and the allocation of samples to cooking batches was recorded. Subsequent to cooking, all samples were cooled in running water for 30 min. The day after cooking, batches was recorded. Subsequent to cooking, all samples were cooled in running water for 30 min. The day after cooking, six samples \(\sim 3\text{--}4 \text{ cm long and } 1 \text{ cm}^2\) in cross-sectional area were cut from each sample, ensuring that the muscle fibres ran along the long axis of the sample and avoiding any fat or connective tissue.

**Shear force measurement**

A texture analyser (Lloyd Instruments, Hampshire, UK; Model LRX at Cowra and LF-Plus at Werribee) set at a cross head speed of 300 mm/min (Werribee) or 200 mm/min (Cowra) and fitted with a 1 kN load cell (both sites) and an inverted V-blade positioned perpendicular to muscle fibre orientation was used to shear the samples.

**Compression measurement**

The force and work associated with passage of a 0.63 cm diameter plunger 0.80 cm through a 1 cm thick meat sample positioned so that the muscle fibres were perpendicular to the direction of the plunger movement were measured. The crosshead speed was set at 50 mm/min with a 1 kN load cell fitted to the texture analyser (Lloyd Instruments, Hampshire, UK at both sites). The plunger was then withdrawn and returned to the same damaged area to measure the reduction in the amount of work done. The computer program attached to the Lloyd Instrument calculates Work 1, Load 1 and Total Work. Compression was calculated using the following equation:

\[
\text{Compression} = \left(\frac{\text{Total Work} - \text{Work 1}}{\text{Load 1}}\right) \times \text{Load 1} \times \text{Work 1} \times \text{N (Bouton and Harris 1972)}.
\]

**Collagen (hydroxyproline)**

The method for measuring total collagen level was described by Colgrave et al. (2008).

**Retail colour**

Retail colour measurements were conducted on samples from flocks 3, 4, 5 and 8 and commenced 5 days post-slaughter, which coincided with the second shear force measurement (SF5). To simulate retail display, each sample was re-sliced to a thickness of 3 cm to provide a fresh surface, placed on a black styrofoam tray (12 x 12 cm), bloomed for 30–40 min and then overwrapped with oxygen permeable polyvinyl chloride film of 15 μm thickness. Samples were held in a chiller for 2 days at 3–4°C under constant lighting at the surface of the meat (~1000 Lux using a 58 W Nelson fluorescent tube for meat display). Colour was measured on day 1, day 2 and day 3 of display using a Hunter Laboratory Mini Scan instrument (Model 45/0-L; aperture size = 25 mm, illuminant D65, standard observer 10°, calibrated with black and white tiles). Measurements were taken without removing the overlap, replicated once after rotating the spectrophotometer 90° in the horizontal plane and the mean of these 2 readings was used for analysis. The oxy/met ratio was calculated by dividing the percentage of light reflectance at a wavelength of 630 nm by the percentage of light reflectance at a wavelength of 580 nm (Hunt et al. 1991) and was calculated for days 1, 2 and 3 of display. The oxy/met ratio on day 3 of display was defined as the retail colour stability.

**Iron, copper, myoglobin and intramuscular fat**

Intramuscular fat level in the LL was measured on a freeze-dried then finely ground sample, using a near infrared procedure in a Technicon Infralyser, as described by Perry et al. (2001). For mineral analysis, freeze-dried samples were prepared according to the USEPA method 200.3 (USEPA 1991). Iron, copper and zinc concentrations were determined on a Vista AX CCD simultaneous ICP-AES (Varian Australia Pty Ltd). Intramuscular fat in the SM was measured by the freeze-dried sample being finely ground, then intramuscular fat content determined by method 1 in Perry et al. (2001), using diethyl ether for extraction. Myoglobin was measured by the method of Trout (1991).

**Data**

The data used and descriptive statistics for each trait are shown in Table 1. A total of 2052 animals were slaughtered for phenotyping and for each of the traits, there were missing data. The range in the data, as indicated by the minimum and maximum values reflect the large variation that have been produced as part of the design.

**Statistical analyses**

The restricted maximum likelihood method was used for all data analyses with flock (Flocks 1, 3, 4, 5, 6, 7 and 8), slaughter date nested within flock, sex (wether, female), age of dam (2, 3, 4, 5, 6 or \(\geq 7\) years), dam breed (Merino or crossbreed), birth-rear...
type (11, 21, 22, 31, 32, 33, with the first number being the number of lambs born and the second number being the number of lambs reared) and sire type (Merino, maternal or terminal) and interactions thereof, where appropriate, as fixed effects. Sire and dam were included in all the models as random effects and allowing separate residual variance for each flock by slaughter batch was also included as a random term. Data were transformed using the natural log for SF1, SF5, compression and collagen, due to non-heterogeneity of variance. For all analyses, terms were included only if they were statistically significant ($P < 0.05$). All statistical analyses were performed using Genstat software (12th Edition, VSN International Ltd, Hemel Hempstead, UK).

The following covariates were tested in the models for SF1, SF5 and compression: hot carcass weight, fat depth at the GR site, pH24 (pH measured at ~24 h in the m. longissimus lumborum, LL), pH18 (pH in the LL at 18°C), pH6temp (temperature of loin muscle at pH6; Pearce et al. 2010), intramuscular fat (IMF) in the loin (for shear force) or SM (for compression and collagen) and combinations of covariates. In the final models, IMF, pH18 or pH24 were included as covariates in the models for SF1 and SF5, SF1–SF5 and IMF in the SM was included as a covariate in the final model for collagen. As pH24 was used to calculate pH18, it was not valid to include both covariates in a model. Therefore, the models are presented with either pH18 or pH24 included as a covariate. The following covariates were tested in the models for retail colour, $L^*$, $a^*$ and $b^*$: hot carcass weight, fat depth at the GR site, pH24, pH18, intramuscular fat (IMF) in the loin, copper, myoglobin or iron, and combinations of covariates. In the final model for $L^*$, $a^*$ and $b^*$, pH24 and myoglobin were included as covariates. The final model for retail colour included IMF, copper, pH18 and iron as covariates.

### Results

#### Consumer acceptability of meat

The predicted acceptability of the tenderness and colour of the meat is presented in Table 2. On day 1 post-slaughter, the proportion of acceptable tenderness among flocks ranged from 0.5% for flock 1 to 58% for flock 8. On day 5 post-slaughter (i.e. after 5 days of ageing), most flocks produced acceptably tender meat (71–95% of samples were acceptable), except for flock 1, of which only 11% of carcasses had acceptably tender meat.

Measurement of the fresh meat colour indicated that all of the samples measured would, on average, be considered to have acceptable redness ($a^* > 9.5$). Furthermore, 90% of all INF samples had an $a^*$ value greater than 14.5 (Table 2), indicating that the majority of samples would be considered to have acceptable redness by 95% of consumers. Flocks 4 and 5 had a lower percentage of carcasses with acceptable fresh meat colour. The percentage of lambs with an oxy/met value below the threshold level for consumer acceptance was 2.3%, 12.3% and 44.8% after 1, 2 and 3 days of display, respectively (Fig. 1). After 3 days of display, the acceptability of the colour of the meat varied from 37 to 61% between the flocks (Table 2).

#### Tenderness traits

**Shear force**

Flock and slaughter date affected SF1, SF5 and SF1–SF5 ($P < 0.001$; Fig. 2 for SF5). Flock 1 produced carcasses that had the highest average shear force on day 1 post-slaughter (51.9 N)

### Table 1. Number, mean, standard deviation (s.d.), minimum and maximum for the traits measured and for the covariates for the muscles Longissimus lumborum (LL) and semimembranosus (SM)

<table>
<thead>
<tr>
<th>Traits</th>
<th>Number</th>
<th>Muscle</th>
<th>Mean ± s.d.</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear force at day 1 (N)</td>
<td>1705</td>
<td>LL</td>
<td>33.25 ± 10.82</td>
<td>11.71</td>
<td>85.6</td>
</tr>
<tr>
<td>Shear force at day 5 (N)</td>
<td>1830</td>
<td>LL</td>
<td>23.64 ± 8.22</td>
<td>10.76</td>
<td>75.61</td>
</tr>
<tr>
<td>Shear-diff (N) (SF1–SF5)</td>
<td>1582</td>
<td>LL</td>
<td>8.76 ± 8.15</td>
<td>−21.91</td>
<td>46.60</td>
</tr>
<tr>
<td>Compression (N)</td>
<td>1979</td>
<td>SM</td>
<td>10.14 ± 2.49</td>
<td>4.65</td>
<td>22.00</td>
</tr>
<tr>
<td>Collagen (g/kg wet tissue)</td>
<td>2007</td>
<td>SM</td>
<td>3.136 ± 0.10</td>
<td>0.703</td>
<td>11.12</td>
</tr>
<tr>
<td>Oxy/met ratio$^a$</td>
<td>1198</td>
<td>LL</td>
<td>3.52 ± 0.76</td>
<td>2.00</td>
<td>6.33</td>
</tr>
<tr>
<td>Lightness ($L^*$)</td>
<td>1753</td>
<td>LL</td>
<td>33.47 ± 2.72</td>
<td>24.43</td>
<td>42.78</td>
</tr>
<tr>
<td>Redness ($a^*$)</td>
<td>1752</td>
<td>LL</td>
<td>17.85 ± 2.58</td>
<td>9.80</td>
<td>23.94</td>
</tr>
<tr>
<td>Yellowness ($b^*$)</td>
<td>1753</td>
<td>LL</td>
<td>4.32 ± 3.78</td>
<td>−5.37</td>
<td>19.37</td>
</tr>
</tbody>
</table>

**Traits**

| pH at 18°C                       | 1874   | LL     | 6.11 ± 0.21 | 5.35 | 6.77 |
| pH at 24h                        | 1911   | LL     | 5.67 ± 0.14 | 5.22 | 6.31 |
| Intramuscular fat (%)            | 2008   | LL     | 4.25 ± 1.00 | 1.50 | 9.09 |
| Intramuscular fat (%)            | 1795   | SM     | 3.11 ± 0.30 | 2.38 | 4.33 |
| Iron (mg/kg wet tissue)          | 1994   | LL     | 20.45 ± 4.39 | 8.12 | 45.11 |
| Copper (mg/kg wet tissue)        | 1994   | LL     | 1.21 ± 0.24 | 0.56 | 3.87 |
| Myoglobin (mg/g wet tissue)      | 1976   | LL     | 6.48 ± 1.98 | 2.15 | 15.62 |

$^a$Oxy/met ratio is the ratio of oxymyoglobin to metmyoglobin in the surface of the LL and is calculated as the reflectance at 630 nm divided by the reflectance at 580 nm.
Table 2. Percentage of m. longissimus lumborum samples acceptable to consumers based on objective measurements for tenderness, fresh colour and retail colour

<table>
<thead>
<tr>
<th>Flock</th>
<th>Number</th>
<th>Tenderness (Newtons)</th>
<th>Fresh meat redness</th>
<th>Retail colour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SF1 &lt; 27$^a$</td>
<td>SF5 &lt; 27$^a$</td>
<td>$a^* &gt; 14.5^b$</td>
</tr>
<tr>
<td>Flock 1</td>
<td>247</td>
<td>0.41</td>
<td>11.11</td>
<td>100.00</td>
</tr>
<tr>
<td>Flock 3</td>
<td>292</td>
<td>7.19</td>
<td>77.05</td>
<td>100.00</td>
</tr>
<tr>
<td>Flock 4</td>
<td>297</td>
<td>26.57</td>
<td>76.79</td>
<td>71.38</td>
</tr>
<tr>
<td>Flock 5</td>
<td>199</td>
<td>56.83</td>
<td>85.79</td>
<td>60.63</td>
</tr>
<tr>
<td>Flock 6</td>
<td>294</td>
<td>45.61</td>
<td>94.52</td>
<td>96.96</td>
</tr>
<tr>
<td>Flock 7</td>
<td>269</td>
<td>37.70</td>
<td>80.60</td>
<td>97.23</td>
</tr>
<tr>
<td>Flock 8</td>
<td>415</td>
<td>58.42</td>
<td>71.20</td>
<td>100.00</td>
</tr>
</tbody>
</table>

$^a$Hopkins et al. (2006) stated that if the shear force is <27 N, a failure rate of no more than 10% will occur for loin meat when eaten.

$^b$Khliji et al. (2010) stated that if oxy/met > 14.5, there is 95% confidence that a randomly selected consumer would find the meat colour acceptable.

$^c$Khliji et al. (2010) stated that if the oxy/met ratio used was after 3 days of simulated retail display. The oxy/met ratio used was after 3 days of simulated retail display.

$^d$Nm = not measured.

$^e$Oxy/met is the ratio of oxymyoglobin to metmyoglobin in the surface of the LL and is calculated as the reflectance at 630 nm divided by the reflectance at 580 nm.

Fig. 1. The % of longissimus lumborum (LL) samples with oxy/met < 3.3 (bar graph) and the mean oxy/met value (●, vertical bar represents standard error) for each day of display. Samples were aged for 4 days before retail display. Oxy/met is the ratio of oxymyoglobin to metmyoglobin in the surface of the LL and is calculated as the reflectance at 630 nm divided by the reflectance at 580 nm.

and on day 5 post-slaughter (35.7 N; Fig. 2). Flock 1 also had a high average shear difference relative to those of flocks 6 and 7. As described above, only 11% of LL samples from flock 1 could be considered tender after 5 days of ageing. Flocks other than flock 1 had similar tenderness values after 5 days of ageing and 75% of the LL samples would have been considered tender after 5 days of ageing.

Females produced LL meat that had a lower shear force on days 1 and 5 post-slaughter and a lower shear force difference than wethers (32.5 v. 33.8 for SF1; 23.4 v. 24.1 for SF5; 8.14 v. 8.94 for SF1-SF5, respectively, back-transformed, so SE not given; $P < 0.05$). Lambs from Merino dams produced meat with 2.5N lower shear force values on day 1 post-slaughter than lambs from cross-bred dams (31.9 v. 34.4; $P < 0.05$), which has not been reported previously. The 7- to 8-year-old dams produced lambs with LL meat that had a higher shear force difference (indicating greater proteolysis) than lambs from younger dams (12.8 v. 8–9.5 N respectively, no SE as back-transformed data; $P < 0.05$).

The IMF content and the pH24 or pH18 influenced shear force values on days 1 and 5 post-mortem and the shear force difference ($P < 0.05$; Table 3). The model predicted that if IMF were to increase from 3.0% to 6.0%, SF1 and SF5 would decrease by 9.9 N and 8.7 N, respectively, and that the shear force difference would decrease by 1.7 N (see Fig. 3). As the traits SF1 and SF5 have been transformed before analysis, it is not possible to use the coefficients in Table 3 to estimate the effects on SF1 and SF5. Instead, the data in Figs 3 and 4 should be used. The model also predicted that if the ultimate pH were to increase from 5.3 to 5.8, SF1 and SF5 would increase by 9.7 N and 5.4 N respectively (Fig. 4). If pH24 is replaced by pH18 in the model, an increase in pH18 from 5.8 to 6.3 increases the SF1 and SF5 by 4.1 N and 4.5 N, respectively (Fig. 4).

Compression

Flock affected SM compression ($P < 0.001$); flocks 1, 3 and 8 had slightly higher values than flocks 4 to 7. As discussed previously, slaughter date nested within flock also had a significant effect on compression ($P < 0.001$). Terminal sires had higher compression values than Merino sires (10.1 v. 9.0 respectively, no SE as back-transformed data; $P < 0.05$), but the difference was small.

Total collagen

There was a significant effect of flock, and slaughter date nested within flock, on the total collagen content of the SM ($P < 0.001$). The main difference was that flock 8 had a higher...
total collagen content than the other flocks. IMF in the SM had a significant effect on collagen concentration ($P < 0.001$; Table 3); an increase in IMF from 3% to 6% corresponded with an increase in collagen concentration of 1.0%. The collagen level was not associated with compression or shear force ($P > 0.05$).

**Fresh colour**

Flock and slaughter date had significant effects on all fresh colour parameters ($P < 0.001$). There was a wide range in colour and there was no clear association between slaughter date and flock, as shown in Fig. 2 using $L^*$ as an example. Female carcasses were 0.26 units darker than wether carcasses ($P < 0.001$; 33.50 v. 33.76 ± 0.085). The birth-rear type had a significant effect on $b^*$ (lambs born as triplets and reared as triplets had lower $b^*$ values), however, birth-rear type was not included in the final model, because of the low numbers of triplets. pH24 was a significant covariate for all fresh colour variables ($P < 0.001$; Table 4). For each 0.1 unit increase in pH24, there was a decrease of 0.18 units in $L^*$, 0.12 units in $a^*$ and 0.22 units in $b^*$. Myoglobin was a significant covariate for $L^*$ ($P < 0.001$) and $a^*$ ($P < 0.005$). An increase of 1 mg/g in myoglobin level was associated with a decrease of 0.23 units in $L^*$ and an increase of 0.04 units in $a^*$.

**Retail colour**

The oxy/met value for each day of display is shown in Fig. 1 and declines over the three days. The oxy/met value after 3 days of display was dependent on flock, slaughter date within flock and dam breed $P < 0.05$. Predicted means for dam breed were 3.39 and 3.65 for Merino and crossbred dams respectively (s.e. = 0.096). Significant covariates for oxy/met were pH18, IMF and iron level on a wet matter basis (mg/g wet weight) and copper level on a wet matter basis (mg/g wet weight) ($P < 0.001$ for all; Table 4). The oxy/met ratio decreased when pH18, IMF and wet matter basis iron and copper levels increased.

**Discussion**

The lambs from the INF are representative of the phenotypic diversity found in the Australian lamb industry and the majority of carcasses (75–95%) would have been acceptable to the consumer for eating quality. Previous work with consumers using best practice production and processing procedures showed that the threshold for acceptability of lamb meat is 27 N (Hopkins et al. 2006). Measurement of the fresh meat colour indicated that all of the samples measured would, on average, be considered to have acceptable redness ($a^*$), assuming a threshold value of 9.5 (Khliji et al. 2010). Flocks 4 and 5 had a lower percentage of carcasses with acceptable colour. This is most likely because the time at which the colour and pH measurements were conducted was only 19–20 h post-slaughter; thus the meat may not have reached a final or ultimate pH. The colour would have been dark until the final pH was reached. This problem has since been rectified by modification of the electrical stimulation system at the abattoir where the INF lambs are slaughtered (Pearce et al. 2010). The potential for improving colour stability is substantial given that the percentage of lambs with an oxy/met value below the
Table 3. Coefficients (s.e. in parentheses) and level of significance (P-value) of the coefficient for covariates in models for shear force on day 1 post-slaughter (SF1), shear force on day 5 post-slaughter (SF5), difference between SF1 and SF5 (SF-diff) and collagen level

<table>
<thead>
<tr>
<th>Intramuscular fat (%)</th>
<th>SF1 (N) (log)</th>
<th>SF5 (N) (log)</th>
<th>SF-diff</th>
<th>Collagen (N) (log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH at 24 h&lt;sup&gt;a&lt;/sup&gt;</td>
<td>P-value</td>
<td>Coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>-0.073&lt;sup&gt;b&lt;/sup&gt; (0.0068)</td>
<td>-0.077&lt;sup&gt;b&lt;/sup&gt; (0.0067)</td>
<td>0.005</td>
</tr>
<tr>
<td>pH at 18°C&lt;sup&gt;c&lt;/sup&gt;</td>
<td>P-value</td>
<td>Coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>0.423&lt;sup&gt;c&lt;/sup&gt; (0.0705)</td>
<td>0.211&lt;sup&gt;c&lt;/sup&gt; (0.0780)</td>
<td>10.70 (2.198)</td>
</tr>
</tbody>
</table>

<sup>a</sup>IMF was measured using the *longissimus lumborum* for SF1, SF5 and SF-diff and using the *semimembranosus* for collagen.

<sup>b</sup>pH24 is the pH measured in the *m. longissimus lumborum* at ~24 h post-slaughter. As pH24 was used to calculate pH18, it was not valid to include both covariates in a model. Therefore, the models are presented with either pH18 or pH24 as a covariate.

<sup>c</sup>pH 18 is the pH measured in the *m. longissimus lumborum* at 18°C and is estimated by linear interpolation (Pearce et al. 2010).

<sup>d</sup>As the traits (SF1, SF5 and collagen) have been transformed before analysis, these coefficients are relevant only for the transformed values. See Figs 3 and 4 for values in the original scale (back transformed values) given certain constraints.

![Fig. 3.](image-url) The effect of intramuscular fat (%) on the predicted shear force for the *longissimus lumborum* at 1 day (SF1) or 5 days (SF5) post-slaughter, after back-transformation. Model for SF5 = Flock + Flock.date + sex + IMF_loin + pH24 LL. Prediction for IMF_loin effect conducted using Flock 1, date 11/12/2007, female and using the mean value for the other covariates.

![Fig. 4.](image-url) The effect of the loin pH at 24 h (pH24) or the loin pH at 18°C (pH18) on the predicted shear force for the *longissimus lumborum* (LL) at 1 day (SF1) or 5 days (SF5) post-slaughter, after back-transformation. Model for SF5 = Flock + Flock.date + sex + IMF_loin + pH24 LL or pH18. Prediction for pH24 LL and pH18 effects conducted using Flock 1, date 11/12/2007, female and using the mean value for the other covariates.

Threshold level for consumer acceptance of 3.3 (Khliji et al. 2010) was 2.3%, 12.3% and 44.8% after 1, 2 and 3 days of display, respectively.

Females produced LL meat that had a lower shear force (more tender meat) on days 1 and 5 post-slaughter and a lower shear force difference than wethers (Hopkins et al. 2006). Previous reports have indicated that ewes produce slightly more tender meat than wethers (Hopkins et al. 2007a; Okeudo and Moss 2008).

Variation in tenderness can mostly be accounted for by sarcomere length at the time of rigor, the extent of proteolysis in the myofibrillar structure and the degree of heat-stable cross linking in collagen (Hopkins and Geesink 2009). Shear force has traditionally been used as an indicator of meat toughness because consumer sensory evaluation of tenderness is expensive. Shear force values on days 1 and 5 can be used to infer conclusions about these characteristics of tenderness. Sarcomere length is determined mainly by the rate of pH and temperature decline prerigor and has a large effect on shear force on day 1 post-slaughter. The change in shear force during ageing can be attributed to proteolysis (Hopkins and Thompson 2002). Shear force 5 days after slaughter is an indicator of basal toughness due to collagen cross linking (Allingham et al. 2006).

The variation between flocks in loin tenderness on day 1 post-slaughter was therefore mostly likely due to non-genetic variations in animal as well as carcass and sample processing...
facts. Predicted shear force values for day 5 samples from flock 1 were high relative to those of other flocks after adjustment for pH18 and pHu. Therefore, pre-rigor pH and temperature conditions do not appear to account completely for this observation. The reason why flock 1 differed from other flocks in this respect remains unclear.

The design of this study was subject to many constraints and this inadvertently led to confounding of some factors for some of the meat traits. In particular, the flock term encompassed more than the site at which the lambs were produced; it included differences due to abattoir and kill date. Kill date was confounded with breed type because Merino lambs were slaughtered last at all sites because their wool characteristics had to be measured prior to slaughter. Apparent differences between Merino and other breeds may have been due to factors associated with kill date, such as animal age and pasture condition.

Variation between slaughter dates in respect of tenderness has been reported previously for cattle (Johnston et al. 2001) and in respect of other meat quality traits in pigs (Purslow et al. 2008). Johnston et al. (2001) proposed that this variation is most likely due to a lack of control over processing conditions. Pearce et al. (2010) showed that electrical stimulation equipment was optimised at only one of the abattoirs used in our study because of malfunctioning electrodes and faster chain speeds than originally used when the units were first installed. As a result, the rate of pH decline varied between abattoirs and was slower than intended for carcasses from six of the seven flocks. Ferguson and Warner (2008) discussed the possibility that variation in tenderness and quality between slaughter dates may be due to variation in the animals’ responses to pre-slaughter stress. In our study, the pre- and post-slaughter protocols were standardised across flocks, although potential for variation still existed for factors such as transport distance. Improvements in electrical stimulation at the abattoirs as described by Pearce et al. (2010) should assist in reducing this variation.

The range in pHu for the loin was small, as 98.9% of pHu values fell between 5.3 and 5.9. Only 1.1% of carcasses had an elevated pHu (pHu > 6.0) in the loin, which is less than the 8% incidence of elevated pHu in lambs reported for New Zealand (Graafhuis and Devine 1994). In Australia, an incidence of 76–83% for elevated pHu carcasses was reported by Jacob et al. (2005) using a cut-off value >5.8 for pHu in the semitendinosus of weaned (carry-over) and unweaned (sucker) lambs. Using the same muscle and pHu cut-off value as Jacob et al. (2005), 40% of our carcasses would be regarded as having a high pHu, but this is most likely because some of the carcasses were measured before an ultimate pH was reached. Using a cut-off for normal pHu in lamb meat of 5.3–5.9, the low incidence (1.1%) of elevated pHu in our study may have been because all flocks followed best practice MSA lamb guidelines (MLA 2007). These guidelines include a pre-slaughter growth rate of >150 g/day, sheep not shorn within 2 weeks of slaughter, processing within 48 h off feed and access to water at all times during on-farm curfew and lairage, except during transport (MLA 2007). Despite the narrow range in pHu, there was a small but significant effect of pHu on the shear force of loins on days 1 and 5 post-slaughter. This effect is consistent with the results of other researchers (Purchas and Aungsupakorn 1993; Devine 1994), who showed that toughness increases as pHu increases from 5.5 to 6.0. Our data showed that the effect of pHu on meat tenderness was reduced by ageing; a similar effect was observed by Devine (1994). It is also likely that some of the loins with an elevated pHu (5.7–5.9) had not reached their final pH. Thus, this relationship may be an indication of cold-shortening, as muscles going through rigor >12 h post-slaughter are most likely to be subjected to cold-shortening if chilling conditions are severe, which was the case at most of the abattoirs used in this study.

There was also a small but significant effect of pH18 on the shear force of loins on days 1 and 5 post-slaughter. pH18 is a measure of the rate of pH fall, such that if the value is high, the rate of pH fall would be slow, and the carcass would be more likely to cold-shorten and produce tough meat. These results are similar to those of Thompson et al. (2005) who measured temperature at pH6 to define the rate of pH and temperature

Table 4. Coefficients (s.e. in parentheses) and level of significance (P-value) of the coefficient for covariates in models for the longissimus lumborum fresh meat colour (L*, a* and b*) measured at 24 h post-slaughter and retail colour measured after 4 days of ageing (5 days post-slaughter) and 3 days of retail display (oxy/met)

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Number</th>
<th>Oxy/met*</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intraduscular fat (%)</td>
<td>P-value</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td>-0.100 (−0.021)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH at 24 h</td>
<td>P-value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td>-0.23 (0.030)</td>
<td>-1.18 (0.261)</td>
<td>-2.22 (0.286)</td>
<td></td>
</tr>
<tr>
<td>pH at 18°C</td>
<td>P-value</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td>-0.759 (0.1336)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron content (mg/kg wet weight)</td>
<td>P-value</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td>-0.097 (0.0058)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper content (mg/kg wet weight)</td>
<td>P-value</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td>-0.330 (0.0825)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myoglobin (mg/kg wet weight)</td>
<td>P-value</td>
<td>&lt;0.001</td>
<td>&lt;0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient</td>
<td>-1.84 (0.500)</td>
<td>0.04 (0.015)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Oxy/met is the ratio of oxymyoglobin to metmyoglobin in the surface of the LL and is calculated as the reflectance at 630 nm divided by the reflectance at 580 nm.
fall and found a similar increase in toughness of lamb loin with slower rates of pH fall. The range in pH18 from 5.6 to 6.6 across the carcases in this study would approximately correspond to a temperature at pH6 of 5°C to 32°C. As cold-shortening occurs if the temperature at pH6 is <10–12°C, it is quite clear that some of the carcases were cold-shortened, which is confirmed in Pearce et al. (2010).

The relationship between fresh colour and pHu is equivocal. Some studies have reported a poor relationship between fresh colour and pHu (e.g. Menzies and Hopkins 1996) and others have reported significant negative correlations between pHu and L*, a* and b* (Hopkins and Fogarty 1998; Fogarty et al. 2000). In our study, pHu was a significant covariate for all fresh colour parameters and the effect was greatest for b*. In addition, myoglobin was a significant covariate for L* and a*. A similar relationship exists for age: older lambs have a darker colour (Hopkins et al. 2007a) and a higher level of myoglobin (Pethick et al. 2005b) than younger lambs.

IMF influenced the shear force traits. For an increase in IMF of 3.5% (the majority of the lambs varied in their IMF from 3.0 to 6.5%), shear force at 5 days post-slaughter decreased by over 10 N. This was not expected and implies that IMF is potentially involved in modifying the structural and enzymatic components of the muscle cytoskeleton and the interaction of these components with the collagen compartment, which together determine meat tenderness. The statistical model for IMF predicted a similar decrease in shear force at 1 and 5 days post-slaughter (9.9 N and 8.7 N respectively) with an increase from 3.0% to 6.0% IMF. This suggests that within this range, IMF is not associated with the proteolytic components of meat tenderisation. Indeed, the negative correlation observed with shear force difference between 1 and 5 days post-slaughter (modelled as −1.7 N) indicates that increasing IMF (from 3.0% to 6.0%) reduces the tenderness of meat as measured by change in shear force between 1 and 5 days post-slaughter. This would be consistent with lamb at 6.0% IMF having lower day 1 shear force values and having less potential change in shear force with ageing to 5 days post-mortem, rather than IMF influencing the proteolytic components of meat tenderisation directly. Our findings support a hypothesis that IMF influences the contribution of the structural components of muscle, including the collagen compartment, to meat tenderness and that IMF does not influence the tenderness of meat during ageing per se. In addition, although IMF was correlated with hot carcass weight (see Pethick et al. 2010), for a 20 kg difference in hot carcass weight, the IMF only changes by 1%, thus not explaining the substantial change in shear force we saw for a 3% change in IMF. This requires more careful investigation to unravel what mechanism is operative given the impact on eating quality as shown previously (Hopkins et al. 2007b).

Hopkins et al. (2006) recently showed that an IMF level of 5% is required to achieve ‘better than every day’ eating quality for sheep meat, but this in it itself explained a very small amount of the variation in eating quality. Generally, palatability increases as IMF content increases. An IMF content of less than 3% has a particularly detrimental effect on palatability. Savell et al. (1986) reported that meat with a fat content of 3–7.3% is generally considered acceptable. Australian lamb contains 4–5% IMF, and studies have demonstrated that this level of fat is required to achieve consumer satisfaction in Australia (Hopkins et al. 2006; Pethick et al. 2007). The average level of IMF in the m. longissimus thoracis et lumborum of the carcases in this study was within the Australian target range for consumer satisfaction (4–5%); the IMF contents of individual carcases ranged from 1.5 to 9.0%. As IMF in the SM increased, the collagen concentration also increased but there was no corresponding decrease in compression values. The collagen values observed in this study were comparable to those of other studies (Young et al. 1993), but the collagen level was not associated with compression or shear force. Nakamura et al. (2010) showed that in beef cattle, shear force and the collagen concentration are positively correlated.

As stated by Harper et al. (1999), the significance of connective tissue in the determination of meat eating quality attributes remains controversial. Some authors have argued that it plays a critical role (Purchas 1972), whereas others consider it to be of limited value as a predictive marker of meat toughness (Tornberg 1996). Lepetit (2007) recently presented convincing evidence that the number of collagen cross-links plays an important role in determining eating quality and that total collagen concentration alone is of little use in predicting eating quality. Although IMF affects collagen level, this is most likely because IMF is deposited in the connective tissue perimysium. Because compression had low heritability (Mortimer et al. 2010), it was not associated with other traits and varied little, a decision was made not to measure this trait in future IMF progeny studies. Total collagen level also had a low heritability (Mortimer et al. 2010) and was not related to other traits. It has been recommended that total collagen level in combination with collagen cross-link level is a useful measurement, and that the collagen cross-link level is more useful than the total collagen level. Thus, it was decided that total collagen level alone was not a valuable trait and measurement of this trait was also terminated.

Recently, the relationship between consumer acceptability and colour of fresh meat measured was assessed using a Minolta chromameter (Khliji et al. 2010). It was concluded that fresh meat colour is considered acceptable on average when the a* (redness) and L* (lighness) values are equal to or exceed 9.5 and 34, respectively. According to these levels, 100% of the IMF samples had acceptable redness and 46% had acceptable lighness. The variation between flocks and the interaction with slaughter date for fresh colour were mostly likely due to the effects of several factors, including the age of animal at slaughter, pre-slaughter nutrition, processing plant effects and measurement protocol. The most important of these would be the age of the animal and pre-slaughter nutrition due to effects on the concentration of myoglobin in the muscle, and the ultimate of the meat, respectively.

Meat from older lambs has more pigment and a darker colour than that from younger lambs (Pethick et al. 2005b). In the 2007 IMF slaughterings, lambs varied in age from 5 months to 14 months, becoming hoggets at 10–12 months of age. In addition, lambs were finished using different systems (Ponnampalam et al. 2010). Carcasses from lambs finished using high-energy pelleted diets have less redness compared with those from lambs fed low-energy diets and pasture (Pethick et al. 2005a). There were differences in the efficiency.

References...
of electrical stimulation between processing plants (Pearce et al. 2010), which has been shown to affect a fresh colour values (Toohey et al. 2008). These effects will be investigated when data from subsequent drops of progeny become available.

Meat from Merinos can be lighter, less red and more susceptible to discolouration than that from other breeds (Warner et al. 2007b). However, due to the confounding of slaughter date with breed in this analysis, it was not possible to examine the relationship between fresh colour and breed. Results from these flocks suggest that colour stability has moderate heritability (Mortimer et al. 2010) and this, together with the significant sire effects, suggests that colour is likely to be responsive to genetic selection. In general, Merinos take more time to reach slaughter weight than other breeds (Ponnampalam et al. 2008) under a given nutritional regime and thus will generally be older than other breeds at slaughter and have darker meat, but if slaughtered at the same age as other breeds no significant difference has been found in colour measures (Hopkins et al. 2007a).

The lower the oxy/met value, the browner and less acceptable the colour of lamb meat is to consumers. If the colour stability of the meat from lambs in the INF can be assumed to be representative of that of the industry, then the cumulative frequency data could provide a quantitative estimate of the extent of the colour stability issue for the Australian industry as a whole. For the INF lambs, 32.5% of the meat samples had oxy/met values that were less than the benchmark value of 3.3 (Khlji et al. 2010) between days 2 and 3 of retail display. Extension of shelf life from 1 to 2 days could therefore potentially apply to one-third of the meat displayed on shelf for this period.

Although the differences between sites and between kill dates indicate that colour stability was strongly influenced by non-genetic as well as genetic factors, this finding provides little insight into the underlying causative factors. Factors such as site and slaughter date are very broad descriptors and more detailed descriptors are needed to manipulate colour stability using animal management strategies. The correlation of IMF with oxy/met could be due to oxidation of myoglobin to metmyoglobin during lipid peroxidation, implying that higher levels of IMF promote oxidation. There is no evidence for this, but there is evidence that unsaturated fatty acids are more prone to oxidation (Faustman et al. 2010). As a result the relationship between IMF and the saturation of fatty acids needs further investigation, given the need to maintain IMF levels for eating quality, but also the attention consumers are paying to omega-3 fatty acids (Lamb et al. 2010). Copper and iron are potential pro-oxidants and may facilitate post-mortem lipid peroxidation (Faustman et al. 2010). Although these correlations are interesting, their magnitudes were relatively small compared with the effect of flock. Other factors not measured in this study such as the concentration of vitamin E in the muscles might also account for differences associated with flock and slaughter date. Future analyses intend to explore more detailed dietary and environmental differences between flock and slaughter date.

The apparent difference in colour stability between the Merino and other sire types was confounded by age, making it difficult to explain. Merino genetics is likely to produce meat of poor colour stability if the animals are older than other breeds at the time of slaughter. Warner et al. (2007b) reported that the loin of 14- and 22-month-old Merinos developed an unacceptably brown colour more quickly than that of first- and second-cross lambs. This was not the case for the knuckle or for 8-month-old lambs. There is a need to clarify the cause of this effect and to design strategies that improve the colour stability of Merino meat.

**Conclusions**

Management of production and processing factors could have a large impact on the tenderness, fresh colour and colour stability of lamb meat. Higher muscle IMF, good pre-slaughter nutrition (resulting in low ultimate pH) and moderate pH-temperature fall (to prevent cold-shortening) are most important non-genetic factors influencing lamb meat tenderness. The majority of lamb loin meat was acceptably tender after five days of ageing. The most important determinant of fresh colour, once the flock and slaughter date variation were accounted for, appeared to be achieving a low ultimate pH. Most of the lamb loin meat was acceptable in terms of fresh meat colour. High IMF and high iron and copper levels in the muscle increased the accumulation of metmyoglobin, and thus the rate browning of meat during retail display. This interaction requires further investigation.

**Acknowledgements**

The authors gratefully acknowledge the contributions of the many staff involved. This project has been a very large collaborative effort involving teams of scientists and technical officers from 7 different research agencies working at 8 information nucleus flock sites, 5 abattoirs, and 7 laboratories across Australia. Individual staff are not listed simply because of the number involved, but their contributions are duly acknowledged. Flock management and data collection have been an essential part of this study that would not have occurred without the dedication and efforts of these people.

**References**


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