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The wool production and reproduction of Merino ewes can be predicted from changes in liveweight during pregnancy and lactation

M. B. Ferguson[A,D,E,H], *A. N. Thompson*[A,D,E], *D. J. Gordon*[A,F], *M. W. Hyder*[B], *G. A. Kearney*[A,G], *C. M. Oldham*[C] and *B. L. Paganoni*[C]

[A]Department of Primary Industries Victoria, Private Bag 105, Hamilton, Vic. 3300, Australia.
[B]Department of Agriculture and Food Western Australia, 444 Albany Highway, Albany, WA 6330, Australia.
[C]Department of Agriculture and Food Western Australia, 3 Baron-Hay Court, South Perth, WA 6151, Australia.
[D]Present address: Department of Agriculture and Food Western Australia, 3 Baron-Hay Court, South Perth, WA 6151, Australia.
[E]Present address: School of Veterinary and Biomedical Sciences, 90 South Street, Murdoch University, Murdoch, WA 6150, Australia.
[F]Present address: Rural Industries Skills Training, Private Bag 105, Hamilton, Vic. 3300, Australia.
[G]Present address: 36 Payne Road, Hamilton, Vic. 3300, Australia.
[H]Corresponding author. Email: mark.ferguson@agric.wa.gov.au

Abstract. Defining the nature of the relationship between change in liveweight throughout a breeding cycle and ewe wool production and reproduction would be useful for developing management guidelines for Merino ewes. In this paper we tested the hypotheses that (1) feed on offer has variable effects on liveweight profiles of individual ewes; and (2) liveweight profiles of individual ewes can be used to predict their fleece wool production and reproductive performance. At sites in Victoria and Western Australia in 2001 and 2002, pregnant Merino ewes were exposed to 10 nutritional treatments. In each of the four experiments, ewes in average condition score 3 at artificial insemination were fed to achieve either maintenance or loss of a condition score over the first 100 days of pregnancy before grazing one of five levels of feed on offer between Day 100 and lamb weaning. Across all four experiments, the average difference in ewe liveweight between extreme treatments was: 7.0 kg (range 4.7–8.7 kg) at Day 100 of pregnancy; 11.9 kg (range 4.9–17.8 kg) at lambing; and by weaning was 13.9 kg (range 8.8–22.7 kg). Liveweight at joining and liveweight change during pregnancy and lactation of individual Merino ewes were significantly related to their clean fleece weight, fibre diameter and staple length and thus the second hypothesis was supported. Heavier ewes at joining produced more wool that was longer and broader and this effect was consistent across both sites and years. A 10-kg loss in ewe liveweight between joining and mid pregnancy, mid pregnancy and lambing or during lactation reduced clean fleece weight by 0.4–0.7 kg and fibre diameter by 0.5–1.4 um. At the Victorian site, where ewes were shorn in summer, a loss of 10 kg in liveweight between joining and Day 100 of pregnancy reduced staple strength by 5 N/ktex. As expected the influence of food on offer on changes in ewe liveweight was different between years and sites and between late pregnancy and lactation due to a complex group of pasture and animal factors. Therefore, managing changes in ewe liveweight itself rather than feed on offer will achieve more predictable outcomes. A higher liveweight at joining resulted in a predictable improvement in ewe reproductive rate and liveweight at joining was more important than the liveweight profile leading up to joining. This paper has shown that it is possible to predict the differences in wool production and reproductive rate of flocks of Merino ewes if ewe liveweight records at key times are known.

Introduction

Merino sheep production systems in southern Australia often experience large fluctuations in the quantity and quality of pasture available within and between years (Rossiter 1966; Purser and Southey 1984). This variation in pasture feed on offer typically results in ewes losing significant weight and condition at some stage during pregnancy (Kelly 1992; Kleemann and Walker 2005). This affects both the quantity and quality of wool produced (Masters *et al*. 1993; Adams and Briegel 1998; Robertson *et al*. 2000) and the reproductive performance of breeding ewes (Suiter and Fels 1971; Lindsay *et al* 1975; Gunn and Maxwell 1989; Kleemann and Walker 2005). Achieving adequate nutrition for breeding ewes and efficient utilisation of grown pasture and supplement remains a major management challenge for these systems.

A good indicator of nutrition in dry sheep within a growing season is the amount of feed on offer, but its application across seasons and regions is limited due to the influence of other

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pasture characteristics (Thompson *et al*. 1994, 1997; Hyder *et al*. 2002). In addition feed on offer is less reliable after pasture senescence than in the growing phase for predicting dry sheep responses (Willoughby 1959). It is likely that feed on offer will be even less able to predict the responses in breeding ewes due to the variation in energy requirements and intake capacity with the stage of pregnancy and lactation and the number of lambs born and reared. There is a need for a better method to manage the nutrition of breeding ewes.

Changes in sheep liveweight are the product of differences between energy intake and energy requirements and this energy balance also influences wool growth rate and fibre diameter (Cannon 1967; Langlands 1969; Hyder *et al*. 2002). It follows that knowledge of ewe liveweight at key points during the reproductive cycle could be a useful predictor of fleece wool characteristics. In addition, both liveweight at joining and changes in liveweight before joining influence the fertility and fecundity of breeding ewes (Morley *et al*. 1978; Kelly *et al*. 1983; Thompson *et al*. 1985). The nature of the relationships between wool production and reproduction with the change in liveweight of ewes throughout a breeding cycle (liveweight profile) remain largely unknown. However, if these relationships can be determined and are reliable across sites and years then liveweight profiles could be used to develop management guidelines for reproducing Merino ewes. In this paper we test the hypotheses that (1) feed on offer has variable effects on liveweight profiles of individual ewes; and (2) liveweight profiles of individual ewes can be used to predict their fleece wool production and reproductive performance.

Materials and methods

All procedures reported in this paper were conducted according to the guidelines of the Australian Code of Practice for the Use of Animals for Scientific Purposes and received approval from the West Australian and Victorian Department of Agriculture Animal Ethics Committees.

Experimental sites and design

A total of four experiments were conducted in 2001 and 2002 at sites located on commercial properties near Hamilton in Victoria (Vic.; 141.7°E/41′25″, –37.6°S/36′1″) and Kendenup in Western Australia (WA; 117.6°E/37′25″, –34.5°S/29′13″). At the Vic. site there were 30 plots (1.8 ha) blocked into three groups of 10 according to position in the landscape and at the WA site there were 20 plots of variable size (0.8–2.0 ha). Both sites experience predominantly winter–spring rainfall, and dry, hot summers, with a long-term average annual rainfall of 590 and 540 mm for the Vic. and WA sites. Actual rainfall received at the Vic. site was 717 and 548 mm for 2001 and 2002. Rainfall at the WA site was 522 and 466 mm for 2001 and 2002. The pastures on the Vic. and WA sites were based on perennial grasses (*Lolium perenne* and *Phalaris aquatica*) and annual grasses (*Lolium rigidum*), respectively.

A factorial design was used with three (Vic.) or two (WA) replicates of the 10 treatments: (1) two target ewe condition scores (2.0 and 3.0) at Day 100 of pregnancy after being artificially inseminated in condition score 2.5–3.0; and (2) five amounts of feed on offer (800, 1100, 1400, 2000 and >3000 kg DM/ha) from Day 100 of pregnancy until weaning (Vic.) or when pasture growth could no longer maintain feed on offer targets (WA). A timetable of key events is given in Table 1. Plots at both sites were grazed by a core group of ewes and lambs and once feed on offer levels were reached they were maintained near target levels by adding and removing dry sheep (Vic.) or adjusting the area grazed by experimental sheep (WA), based on estimates of feed on offer, anticipated pasture growth rates and estimates of pasture intake, as described by Thompson *et al*. (1994).

Pasture management and measurements

The plots were de-stocked in summer after the residual dry pasture had been grazed to a dry feed on offer of ~1000 kg DM/ha. All plots were fertilised with single superphosphate in February–March of each year at ~30 kg P/ha (Vic.) and 14 kg P/ha (WA) and pasture pests were controlled as required. Pastures at

Table 1. Timetable of key events at research sites in Victoria and Western Australia in 2001 and 2002. The average dates of artificial insemination were considered to be Day 0 for each experiment

Key event	Victoria 2001	Victoria 2002	Western Australia 2001	Western Australia 2002
Average date of artificial insemination	2 April 2001 (Day 0)	29 March 2002 (Day 0)	1 March 2001 (Day 0)	1 March 2002 (Day 0)
Experimental ewes moved onto plots	4 July 2001 (Day 93)	1 July 2002 (Day 94)	6 June 2001 (Day 97)	10 June 2002 (Day 101)
Last weighing before lambing commenced	20 August 2001 (Day 140)	19 August 2002 (Day 143)	17 July 2001 (Day 138)	15 July 2002 (Day 136)
Average date of lambing	30 August 2001 (Day 150)	28 August 2002 (Day 152)	30 July 2001 (Day 151)	30 July 2002 (Day 151)
Experimental ewes and lambs removed from plots	12 November 2001 (Day 224)	12 November 2002 (Day 228)	26 October 2001 (Day 239)	24 October 2002 (Day 237)
Ewe shearing – pre-treatment	23 November 2000 (Day –130)	20 December 2001 (Day –99)	10 April 2001 (Day 40)	12 April 2002 (Day 42)
Ewe shearing – post-treatment	13 December 2001 (Day 255)	20 February 2003 (Day 328)	16 April 2002 (Day 411)	9 April 2003 (Day 404)

the Vic. site were deferred after the break of season and stocked with dry sheep if target feed on offer levels were achieved whereas all pastures at the WA site were totally deferred until allocation of experimental ewes.

Feed on offer was assessed at 1–2-week intervals after the break of season until the end of the experimental period by visual assessment; 30 observations per plot by two observers. The assessments were calibrated using quadrat cuts that covered the range in feed on offer and botanical composition at that time. All green material in quadrats was harvested by cutting to ground level and the harvested samples were rinsed to remove non-vegetative organic matter, dried at 60°C and weighed. Calibrated feed on offer was determined using regression analysis. Pasture composition was estimated at three to five key times in each experiment using the 'toe-cut' method (Cayley and Bird 1996) where at least 30 samples were cut to ground level from small areas randomly selected within each plot. These samples were sorted into perennial ryegrass, phalaris, subterranean clover, annual grasses, onion grass, broadleaf weeds and dead for the Vic. site and subterranean clover, annual grasses, broadleaf weeds and dead for the WA site. These samples were dried at 60°C and weighed to determine botanical composition.

Experimental sheep and management

Approximately 1500 medium wool Merino ewes were used at both sites and different ewes were used each year. Ewes at the Vic. site were 2.5 or 3.5 years old and at the WA site between 2.5 and 5.5 years old. Oestrus was synchronised using progesterone sponges (Chronogest, Intervet, South Africa) and pregnant mare serum gonadotrophin (400 IU/ewe; Folligon, Intervet, South Africa) and ewes were artificially inseminated on 3 or 4 separate days over a 7–10-day period. At each site the average date of insemination was designated as Day 0 of the experiment. Semen was used from four fine-medium wool bloodlines and ~20 sires were used at each site each year. The two sites were linked by sires both within and between years.

Following artificial insemination ewes were allocated to two flocks after stratification for liveweight, condition score and sire source and then managed to achieve target condition score 2 or condition score 3 (Jefferies 1961) by Day 100 of pregnancy by altering grazing pressure and their supplementary feeding regime. About 60 days after artificial insemination all ewes were scanned using real-time ultrasound to determine the number of fetuses (Fowler and Wilkins 1984). At the Vic. site 303 and 375 single- and twin-bearing ewes were retained in the experiment in 2001 and 467 and 219 single- and twin-bearing ewes were retained in 2002. At the WA site 320 single-bearing ewes were retained in each experiment. After pregnancy scanning all ewes that were not required for the experiments were returned to the farm flocks.

Feed on offer treatments commenced around Day 100 of pregnancy when at the Vic. site between 18 and 28 ewes were allocated to plots from within each condition score group (target 2 or 3 at Day 100), after stratification for their liveweight, condition score, sire of progeny, ewe age and litter size (1 or 2). More ewes were allocated to low feed on offer plots. At the WA site 16 ewes from within each condition score group were allocated to plots after stratification for their liveweight, condition score, sire of progeny and ewe age. Treatments were allocated to plots at random within each replicate.

Ewes lambed on the plots and ewes and lambs remained on the plots until around weaning. Following weaning, the ewes at each site grazed together for 14 months at the Vic. site and 6 months at the WA site. Further details on the management of progeny and their measurements and performance from birth to adulthood are reported by Oldham *et al*. (2011) and Thompson *et al*. (2011*a*, 2011*b*). All sheep were drenched with an effective anthelmintic when counts of worm eggs in faeces were at levels sufficient to compromise production and health of any group.

Ewe liveweight and condition scores

Ewes were weighed and condition scored approximately monthly at the Vic. site and 2-weekly at the WA site during pregnancy and lactation, except for a 5–6-week period immediately following artificial insemination when ewes were not handled. They were weighed and condition scored every 1–2 months between weaning and the following shearing (about 2 months in Vic. and 4 months in WA). Liveweight of ewes was adjusted for conceptus weight using the equations of Wheeler *et al*. (1971) and weight of greasy wool estimated using the dyeband technique (Williams and Chapman 1966). Ewes were condition scored by trained operators following the method described by Jefferies (1961). Several operator comparisons were undertaken during the experiments and condition scores were standardised using regression equations between operators, as described by van Burgel *et al*. (2004).

In the analysis for the Vic. site the liveweight of ewes and their condition score gave similar effects on ewe performance. At the WA site, the liveweight of ewes gave similar results to the Vic. site whereas the relationships with their condition score were less clear. Therefore, given the subjective methodology of condition scoring and the variability between operators (van Burgel *et al*. 2004), it was decided to only report on the effects of the liveweight and change in the liveweight of ewes in this paper and in others in the series that report the results of the plot-scale experiments (Oldham *et al*. 2011; Thompson *et al*. 2011*a*, 2011*b*).

Wool measurements and analyses

Dyebands were applied to the mid side of five single- and five twin-bearing ewes per plot at the Vic. site and five ewes per plot at the WA site. They were applied at about monthly intervals between Day 100 of pregnancy and removal from experimental plots around weaning. Ewes were shorn before joining at the Vic. site and during early pregnancy at the WA site, and then again at both sites after the experimental treatments (Table 1). Prior to the second shearing, dyebands were removed at skin level using animal clippers and a wool sample was collected from the mid side of all experimental ewes using a shearing handpiece. Greasy fleece weight, including belly wool, was recorded for all ewes at shearing.

The mid-side samples were analysed for washing yield, mean fibre diameter, coefficient of variation of fibre diameter, staple strength and staple length and position of break along the staple. Clean fleece weight was calculated by multiplication of yield percentage and greasy fleece weight. The clean weight of wool between dyebands was measured on five staples per sheep. Rates of wool growth were calculated using the weight of wool between each dyeband as a proportion of the total weight of the staple multiplied by clean fleece weight. Fibre diameter profiles were measured using an OFDA 2000 (Behrendt *et al.* 2002) at 2-mm intervals for 10 sheep per plot at the Vic. site and 5-mm intervals for all ewes at the WA site.

Statistical analyses

All statistical analyses were performed using GENSTAT (GENSTAT Committee 2008). ANOVA was used to test differences between treatments in feed on offer and botanical composition, ewe liveweight and condition score, liveweight changes and wool growth rates during different periods and the weight and characteristics of fleece wool.

To determine the ewe liveweight change from Day 100 to lambing and lambing to weaning, a range of functions were tested including linear, quadratic, logarithmic and different exponential functions. The exponential function $y = A + BR^x$ where A, B and R are constants, was used to describe the ewe liveweight change y, in terms of actual feed on offer (kg/ha) × while also accounting for condition score group at Day 100 and/or birth and rearing type, provided the most appropriate fit to the data. In this model A is the value of y at the asymptote, B is the range in y between zero feed on offer and the asymptote and R is the rate of exponential increase or decrease in y.

A second analysis of data generated from the four experiments was conducted to determine whether the maternal liveweight or change in maternal liveweight of ewes or feed on offer during specific periods could be used to predict the clean fleece weight, mean fibre diameter, staple length and staple strength of the wool produced by the ewes. Many models were explored to ensure the final modelling provided a statistically sensible parsimonious explanation of the data, in a biologically sound framework. The restricted maximum likelihood model that best predicted the wool production and quality of ewes used the change in liveweight of the ewe between joining and Day 100 of pregnancy, change in liveweight of the ewe from Day 100 of pregnancy until lambing, change in liveweight from lambing to weaning, the rear type and age of the ewes. In this model, ewe age and rear type were fitted as fixed effects where appropriate, and year, replicate, plot and sire were fitted as random effects. All possible models were examined with statistical significance of terms and interactions thereof accepted at $P < 0.05$.

Reproductive rate was analysed for effect of ewe liveweight at joining using a generalised linear model with a multinomial distribution and logit link function and adjusted for ewe age and rear rank during the previous reproductive cycle.

Results

Feed on offer and pasture composition

In all four experiments a wide range of feed on offer profiles were generated and there were no consistent differences in the amount and botanical composition of pastures between ewe condition score treatments at the start of grazing on Day 100 of pregnancy. At the Vic. site most target feed on offer levels were achieved by the start of the grazing treatments and these were maintained until weaning (Fig. 1*a*, *b*). The exception was plots assigned to the 3000 kg DM/ha treatment in 2002, which did not approach the target feed on offer until near the end of the treatment period. The average feed on offer achieved was 950, 1200, 1400, 1900 and 3500 kg DM/ha (l.s.d. 112) in 2001 and 900, 1150, 1400, 2150 and 2300 kg DM/ha (l.s.d. 99) in 2002 for the target feed on offer treatments of 800, 1100, 1400, 2000 and 3000 kg DM/ha, respectively. On average the pastures were of moderate quality with 10% subterranean clover, 25% of perennial ryegrass and phalaris and 15% onion grass (*Romulea rosea*) and there was little variation in pasture composition between feed on offer treatments.

The average feed on offer at allocation of ewes to plots at the WA site was ~1000 and 1300 kg DM/ha in 2001 and 2002, respectively. The levels were similar for all treatments in 2001 but differed in 2002, and in both years the highest feed on offer treatments did not approach the 3000 kg DM/ha target until near the end of the treatment period (Fig. 1*c*, *d*). In 2001 the average feed on offer achieved was 850, 900, 1250, 1750 and 2200 kg DM/ha (l.s.d. 112), for the target feed on offer treatments 800, 1100, 1400, 2000 and 3000 kg DM/ha, respectively. In 2002 the average feed on offer for the different treatments was very close to target levels being 800, 1100, 1300, 1950 and 2900 kg DM/ha (l.s.d. 223). On average the pastures were of high quality with 40% subterranean clover, 25% of annual grasses and 35% of capeweed (*Arctotheca calendula*). There was little variation in pasture composition between feed on offer treatments.

Ewe liveweight profiles

At the Vic. site the average liveweight and condition score of the ewes at or just before artificial insemination in 2001 and 2002 were 46 kg and 2.7 and 45 kg and 3.0, respectively. At the WA site the values were 46 kg and 2.9 and 47 kg and 2.5 in 2001 and 2002, respectively. The treatments imposed generated a wide range of ewe liveweight profiles at the Vic. (Fig. 2*a*, *b*) and WA site (Fig. 2*c*, *d*) in both years. Across all experiments, the average difference in condition score and liveweight of ewes achieved by Day 100 of pregnancy was 0.7 of a condition score (range 0.6–0.9) and liveweight was 7.0 kg (range 4.7–8.7 kg), respectively. All ewes gained liveweight ($P < 0.05$) immediately following introduction to plots, especially those lower in condition score at Day 100 of pregnancy and grazing higher feed on offer. Overall, grazing different amounts of feed on offer from Day 100 of pregnancy amplified the spread in ewe liveweight such that the average difference between extreme treatments was 11.9 kg (range 4.9–17.8 kg) at lambing. The difference between feed on offer treatments increased during lactation and was 13.9 kg (range 8.8–22.7 kg) at weaning. After weaning, ewes grazed together but treatment effect on ewe liveweight was still significant ($P < 0.001$) at the following joining in both years and at both sites.

Twin-bearing ewes at the Vic. site were heavier (47 versus 44 kg; $P < 0.001$) during early pregnancy than single-bearing ewes in 2001 but the difference was no longer significant by lambing. By contrast, there were no significant differences in 2002. In both years, ewes that reared twin lambs were lighter

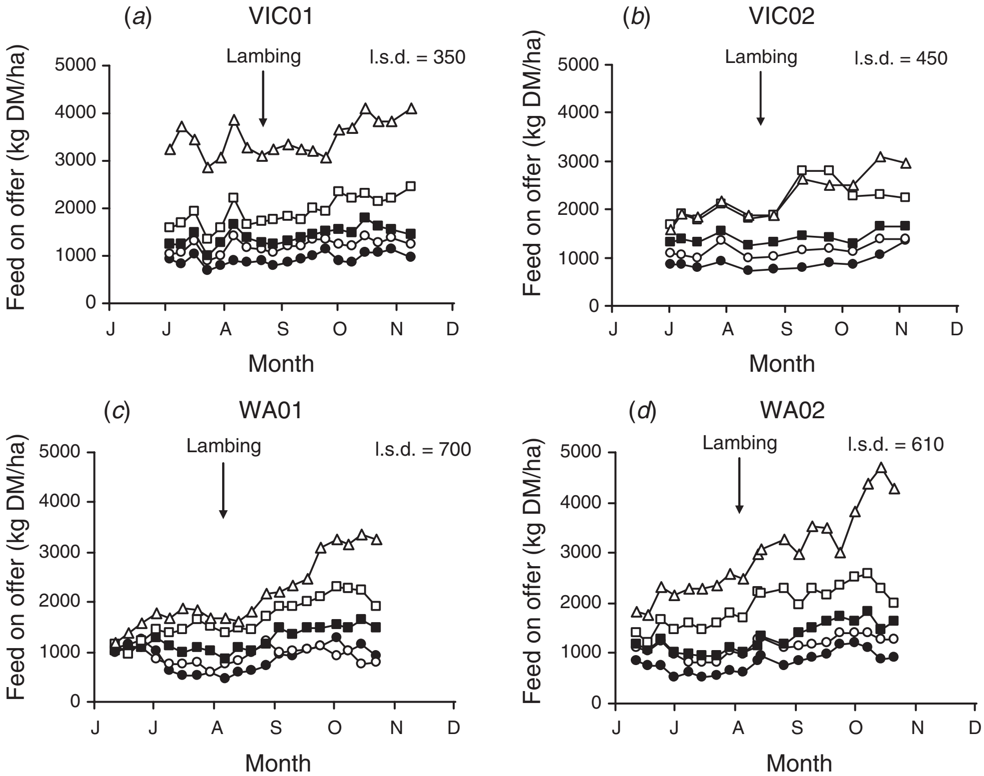

Fig. 1. Average green feed on offer for treatments grazed by Merino ewes to target feed on offer of 800 (●), 1100 (○), 1400 (■), 2000 (□) or 3000 (△) kg DM/ha from Day 100 of pregnancy at the Vic. site in 2001 (*a*) and 2002 (*b*) and the WA site in 2001 (*c*) and 2002 (*d*). The time of lambing (arrow) and the maximum least significant difference (l.s.d.) to compare across time and between treatments is shown on each graph. Plots were grazed by ewes that had been managed to achieve a condition score of 2 or 3 by Day 100 of pregnancy and values represent averages of six plots at the Vic. site and four plots at the WA site.

(45 versus 47 kg; $P < 0.001$) than those that reared a single lamb during lactation and at the following joining.

Treatment effects of fleece wool production and quality

The nutritional treatments influenced ewe fleece wool characteristics in both years and at both sites (Tables 2 and 3). Ewe clean fleece weight, mean fibre diameter and staple length responded to the feed on offer treatment during late pregnancy and lactation, but there was no significant effect ($P > 0.05$) of feed on offer treatment on the coefficient of variation in fibre diameter or staple strength. Improving nutrition during early- and mid pregnancy consistently increased ($P < 0.001$) clean fleece weight by ~0.3 kg, whereas the effects on fibre diameter and staple length were variable between sites and years. Staple strength was significantly increased ($P < 0.001$) by better nutrition between conception and Day 100 of pregnancy at the Vic. site in both years. About 20% of the variance in staple strength (SS) between individual ewes at the Vic. site over both years was explained by minimum fibre diameter (FD_{min}) and along-fibre variation in diameter ($^{A}FD_{cv}$), where:

$$\mathrm{SS\ (N/ktex)} = 11.7(\pm 5.82) + 1.3(\pm 0.27)\,\mathrm{FD_{min}}\ (\mu\mathrm{m}) - 1.2\,(\pm 0.23)\ {}^{A}\mathrm{FD_{cv}}(\%)$$

At the WA site there was no effect of condition score at Day 100 or feed on offer treatment on staple strength, even though ~12% of the variance in staple strength between individual ewes was explained by the minimum fibre diameter along the staple. Each 1-µm increase in minimum fibre diameter resulted in an increase in staple strength of 2.3 N/ktex in staple. The effect of birth type on wool traits at the Vic. site was variable between years. In 2001 the only trait that was significantly affected by birth type was staple strength that was lower in twin-bearing then single-bearing ewes. In Vic. clean fleece weight, mean fibre diameter and staple length were all lower in twin-bearing than single-bearing ewes.

Ewe liveweight and wool growth responses in late pregnancy

Liveweight change between Day 100 of pregnancy and lambing increased curvilinearly ($P < 0.001$) with increasing feed on offer (Table 4). Up to 50% ($P < 0.001$) of the variation in liveweight change between individual ewes was explained by feed on offer, but the relationships were different between sites and years and were influenced by ewe condition score at Day 100 of pregnancy (Fig. 3) and the number of fetuses the ewe was carrying at the Vic. site (Fig. 4; Table 4).

The feed on offer needed to achieve weight gains in excess of 90% of the maximum were 1500–1700 kg DM/ha at the Vic. site

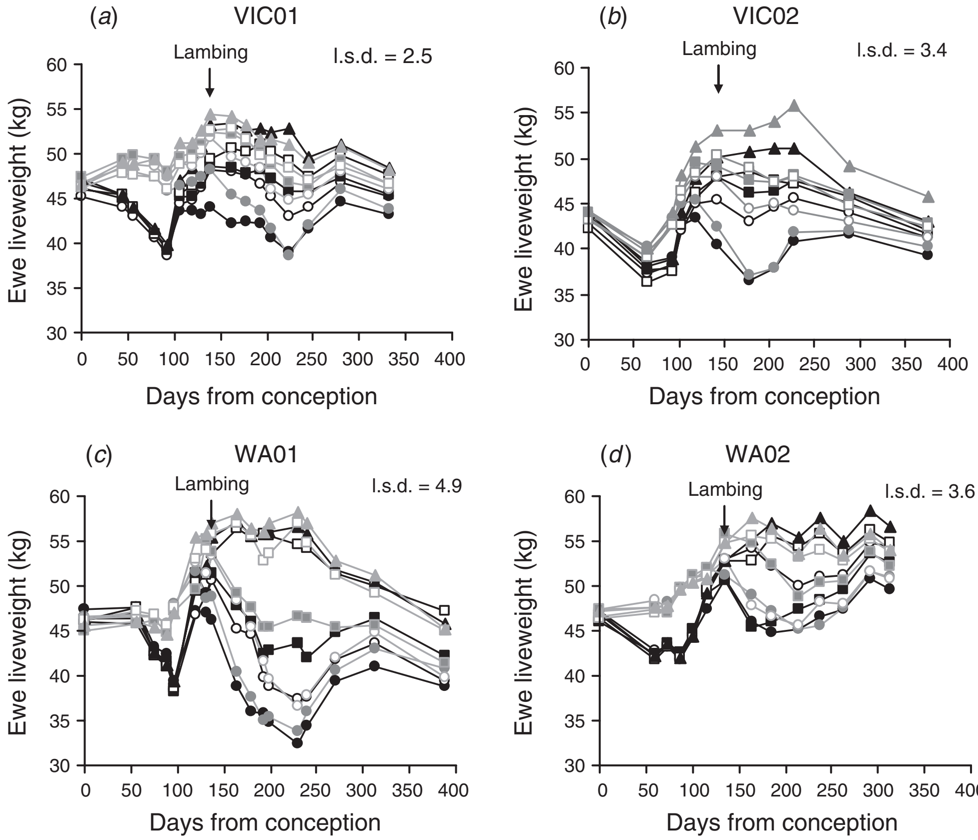

Fig. 2. Average maternal liveweight of Merino ewes managed to achieve condition score 2 (black) or 3 (grey) at Day 100 of pregnancy and then grazed on pastures managed to target feed on offer of 800 (●), 1100 (○), 1400 (■), 2000 (□) or 3000 (△) kg DM/ha during late pregnancy and lactation at the Vic. site in 2001 (*a*) and 2002 (*b*) and the WA site in 2001 (*c*) and 2002 (*d*). The time of lambing (arrow) and the maximum least significant difference (l.s.d.) to compare across time and between treatments is shown on each graph. Values represent averages of three plots at the Vic. site and two plots at the WA site for the period from artificial insemination to the following joining, and only ewes that reared at least one lamb are included. Liveweight was corrected for cumulative wool weight and conceptus and adjusted for differences in ewe age and rearing rank.

and 1100–1300 kg DM/ha at the WA site. In all cases, the maximum gain in liveweight was significantly greater for ewes in condition score 2 at Day 100 of pregnancy than those in condition score 3 and for single compared with twin-bearing ewes at the Vic. site. Ewe liveweight change was most responsive at low feed on offer levels, but with one exception the shape of the response curves was similar irrespective of condition score at Day 100 of pregnancy or birth rank. In 2001 at the Vic. site, ewes in condition score 2 at Day 100 of pregnancy gained significantly more liveweight as feed on offer increased up to the ~1500 kg DM/ha. Single-bearing ewes at the Vic. site gained ~2 kg more weight during late pregnancy than twin-bearing ewes irrespective of feed on offer levels. The predicted feed on offer required for liveweight maintenance (feed on offer at zero change in liveweight) was 600–800 kg DM/ha at the Vic. site and 500–700 kg DM/ha at the WA site (see Figs 3 and 4).

The treatments imposed had significant impacts on wool growth rates per day during late pregnancy at the Vic. and WA site in both years and wool growth rates increased curvilinearly with increasing feed on offer ($P < 0.001$). Across both sites and years ewes managed to a target condition score of 3 at Day 100 of pregnancy grew 1.0–1.5 g/day more wool during late pregnancy than managed to a target condition score of 2 at Day 100 of pregnancy across all feed on offer levels. Twin-bearing ewes at the Vic. site also produced less wool than single-bearing ewes during this time across all feed on offer levels, but the difference was only ~1 g/day.

There was a strong positive linear relationship ($P < 0.001$) between changes in ewe liveweight and wool growth rate during late pregnancy. The intercept of the relationships were similar ($P > 0.05$) for all years and sites, and was greater (11.9 versus 9.1 g/day; $P < 0.05$) for ewes managed to be in condition score 3 compared with those in condition score 2 at Day 100 of pregnancy. The average slope was similar for each year at each site, but differed significantly between sites ($P < 0.05$), being 1.3 versus 0.9 g wool/day per every 100 g/day gain in liveweight for the Vic. and WA sites, respectively. Birth rank had no significant effect on this relationship in 2001 at the Vic. site, but single-bearing ewes produced more wool for the same change in liveweight than twin-bearing ewes in 2002.

Table 2. The mean treatment effect for both years at the Victoria site on ewe clean fleece weight (CFW; kg), mean fibre diameter (FD_{mean}; um), minimum (FD_{min}; um) and along-fibre coefficient of variation in fibre diameter (${}^{A}FD_{cv}$; %), total coefficient of variation of fibre diameter (${}^{T}FD_{cv}$; %), staple length (SL; mm) and staple strength (SS; N/ktex). Single- and twin-bearing ewes were differentially fed to achieve condition score 2 or 3 at Day 100 of pregnancy and then grazed a range of feed on offer levels until weaning

Level of significance; $P < 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ (***). n.s., not significant

	CFW	FD_{mean}	FD_{min}	${}^{A}FD_{cv}$	${}^{T}FD_{cv}$	SL	SS
			2001				
Feed on offer treatment							
800	3.7	20.7	18.7	5.4	20.8	103	29.1
1100	4.0	21.4	19.5	4.9	19.8	108	30.8
1400	4.1	21.4	19.0	5.1	20.4	107	30.3
2000	4.2	21.6	19.3	5.3	20.4	109	29.2
3000	4.4	21.9	19.6	5.5	20.5	108	27.7
s.e.d.	0.10	0.26	0.32	0.33	0.30	1.4	1.29
Level of significance	***	***	$P = 0.06$	n.s.	n.s.	**	n.s.
Condition score Day 100 treatment[A]	0.3***	0.5**	–0.58***	–0.82**	–1.2**	3.4***	9.0***
Birth type[B]	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	–2.3**
			2002				
Feed on offer treatment							
800	3.1	19.4	16.7	7.2	22.0	97	22.1
1100	3.8	20.2	17.0	7.6	21.4	102	24.5
1400	3.8	20.4	17.0	8.0	21.7	103	22.5
2000	3.9	20.5	17.0	8.2	21.5	103	22.7
3000	4.0	20.7	17.0	8.2	21.3	104	23.0
s.e.d.	0.08	0.21	0.31	0.40	0.35	1.3	1.08
Level of significance	***	***	n.s.	*	n.s.	***	n.s.
Condition score Day 100 treatment[A]	0.3**	n.s.	–0.95***	–0.97***	n.s.	2.4**	4.5***
Birth type[B]	–0.3***	–0.3*	n.s.	n.s.	n.s.	–2.6**	n.s.

[A]Significance of the average difference between ewe condition score 2 and 3 at Day 100 of pregnancy treatments.
[B]Significance of the average difference between single- and twin-bearing ewes.

Ewe liveweight and wool growth responses in lactation

The relationship between feed on offer and ewe liveweight change during lactation was curvilinear, with the exception of the Vic. site in 2002 when liveweight change of ewes from all treatments was within 1 kg and the response was not significant. With this exception, approximately 40% ($P < 0.001$) of the variation between individual ewes in liveweight change during lactation within site and year was explained by feed on offer. At the Vic. site in 2001, ewes in lower condition score at Day 100 of pregnancy lost less weight ($P < 0.05$) regardless of feed on offer and ewes rearing twin lambs lost ~2 kg more weight ($P < 0.05$) during lactation than those that reared a single lamb. On average, ewes at the WA site achieved liveweight maintenance during lactation at ~2000 kg DM/ha, but in 2002 those in lower condition score at Day 100 of pregnancy gained ~2.5 kg more weight than those in condition score 3 at Day 100 of pregnancy regardless of feed on offer level ($P < 0.05$).

The positive relationship between feed on offer and wool growth rates during lactation was curvilinear ($P < 0.001$) at the Vic. and WA site in both years. There was no effect of condition score at Day 100 of pregnancy on the response in either year at the Vic. site, but in 2002 ewes that reared a single lamb produced more wool during lactation than ewes that were pregnant with twins and raised one or both lambs (11.0 versus 10.0 versus 10.3 g/day; $P < 0.05$), respectively. At the WA site, ewes managed to be in condition score 3 at Day 100 of pregnancy produced slightly more wool regardless of feed on offer than those in condition score 2 at Day 100 of pregnancy, whereas the opposite occurred in 2002. Surprisingly, with the exception of the WA site in 2001, there were no significant relationships between changes in ewe liveweight and wool growth rate during lactation.

Prediction of ewe fleece wool from the liveweight profile of ewes

Ewe liveweight at joining and ewe liveweight change during pregnancy and lactation were positively related to ewe clean fleece weight, mean fibre diameter and staple length (Tables 5 and 6). Ewe age had a significant impact on these wool traits. The coefficients did not differ ($P > 0.05$) between years at each site and therefore the data from different years was combined for each site. The number of lambs they reared only had a significant impact on the clean fleece weight at the Vic. site. Changes in liveweight of individual ewes from weaning to their next joining were not related to their clean fleece weight, mean fibre diameter or staple length.

Heavier ewes at joining produced more wool that was longer and broader and this effect was consistent across both sites and years. A 10-kg loss in ewe liveweight between joining and mid pregnancy, mid pregnancy and lambing or lactation reduced clean fleece weight by 0.4–0.7 kg and fibre diameter by 0.5–1.4

Table 3. The mean treatment effect for both years at the Western Australia site on ewe clean fleece weight (CFW; kg), mean fibre diameter (FD_{mean}; um), minimum (FD_{min}; um) and the product of a natural log of along-fibre coefficient of variation in fibre diameter ($log^A FD_{cv}$; %; back-transformed values in parentheses), total coefficient of variation of fibre diameter ($^T FD_{cv}$; %), staple length (SL; mm) and staple strength (SS; N/ktex). Single-bearing ewes were differentially fed to achieve condition score 2 or 3 at Day 100 of pregnancy and then grazed a range of feed on offer levels until weaning

Level of significance; $P < 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ (***). n.s., not significant

	CFW	FD_{mean}	FD_{min}	$log^A FD_{cv}$	$^T FD_{cv}$	SL	SS
			2001				
Feed on offer treatment							
800	2.7	18.3	16.1	–0.14 (1.1)	21.3	74	35.3
1100	3.0	19.3	16.9	0.38 (1.5)	22.3	79	38.1
1400	3.5	20.1	17.2	0.72 (2.1)	21.6	82	38.1
2000	4.0	21.4	17.4	1.41 (4.1)	21.4	85	35.4
3000	4.1	21.3	17.0	1.45 (4.3)	21.0	85	37.2
s.e.d.	0.12	0.37	0.42	0.21	0.63	1.6	2.13
Level of significance	***	***	*	***	n.s.	***	n.s.
Condition score Day 100 treatment[A]	0.3***	1.0***	1.0***	n.s.	n.s.	2.8**	n.s.
			2002				
Feed on offer treatment							
800	3.7	20.4	17.6	0.65 (1.9)	19.3	88	39.1
1100	3.9	20.7	17.7	0.74 (2.1)	19.5	89	36.4
1400	3.9	20.9	17.6	0.91 (2.5)	20.0	88	37.8
2000	4.2	21.5	17.5	1.19 (3.3)	19.9	91	37.6
3000	4.3	21.9	18.2	1.23 (3.4)	19.2	92	38.8
s.e.d.	0.13	0.34	0.28	0.20	0.51	1.5	1.89
Level of significance	***	***	$P = 0.06$	*	n.s.	*	n.s.
Condition score Day 100 treatment[A]	0.3**	n.s.	0.7***	n.s.	n.s.	n.s.	n.s.

[A]Significance of the average difference between ewe condition score 2 and 3 at Day 100 of pregnancy treatments.

Table 4. The exponential function ($y = A + BR^x$) describing the relationship between actual feed on offer and ewe liveweight between Day 100 of pregnancy and lambing at the Victoria and Western Australia sites. The ewes were differentially fed to achieve condition score 2 or 3 at Day 100 of pregnancy. In this model A is the value of *y* at the asymptote, B is the range in *y* between zero feed on offer and the asymptote and R is the rate of exponential increase or decrease in *y*

	Condition score 2	Condition score 3	Single-bearing	Twin-bearing
Victoria				
		2001		
A	12.95 ± 0.38	7.05 ± 0.32	11.08 ± 0.42	8.94 ± 0.43
B	–49.7 ± 12.5	–32.8 ± 9.1	–28.94 ± 9.51	–28.94 ± 9.51
R	0.9977 ± 0.0003	0.9977 ± 0.0003	0.9980 ± 0.0004	0.9980 ± 0.0004
		2002		
A	11.84 ± 0.34	8.61 ± 0.37	10.95 ± 0.41	9.50 ± 0.46
B	–121.2 ± 36.9	–121.2 ± 36.9	–92.9 ± 27.6	–92.9 ± 27.6
R	0.9968 ± 0.0004	0.9968 ± 0.0004	0.9971 ± 0.0004	0.9971 ± 0.0004
Western Australia				
	2001		*2002*	
	Condition score 2	Condition score 3	Condition score 2	Condition score 3
A	16.81 ± 0.47	9.28 ± 0.43	11.19 ± 0.38	5.56 ± 0.31
B	–89.2 ± 32.5	–89.2 ± 32.5	–36.1 ± 16.0	–36.1 ± 16.0
R	0.9966 ± 0.0005	0.9966 ± 0.0005	0.9964 ± 0.0008	0.9964 ± 0.0008

um (Tables 5 and 6). At the Vic. site where ewes were shorn in summer a loss of 10 kg in liveweight between joining and Day 100 of pregnancy reduced staple strength by 5 N/ktex. The negative effects of liveweight loss during early to mid pregnancy on staple strength were amplified by gains in liveweight during late pregnancy, such that ewes that lost 10 kg to mid pregnancy and then regained this weight by lambing produced wool that was 7–8 N/ktex weaker than those that

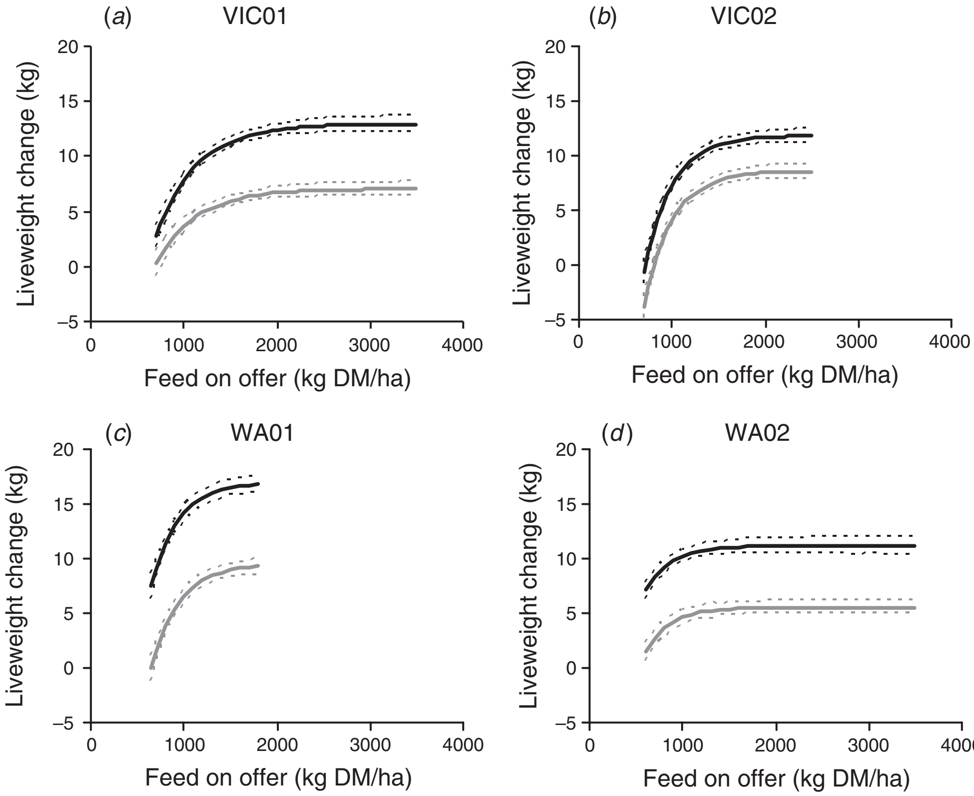

Fig. 3. Effect of average feed on offer from Day 100 of pregnancy to lambing on changes in maternal liveweight at the Vic. site in 2001 (*a*) and 2002 (*b*) and the WA site in 2001 (*c*) and 2002 (*d*). The data is for ewes managed to target condition score 2 (black) or condition score 3 (grey) at Day 100 of pregnancy, and dashed lines represent upper and lower 95% confidence limits. Liveweight was corrected for cumulative wool weight and conceptus. The Vic. data represents the average of single- and twin-bearing ewes.

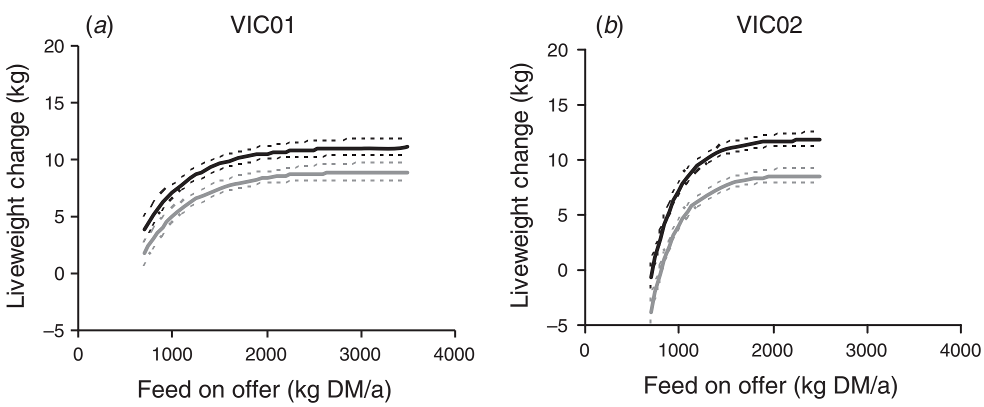

Fig. 4. Effect of average feed on offer from Day 100 of pregnancy to lambing on changes in maternal liveweight at the Vic. site in 2001 (*a*) and 2002 (*b*). The data is for single-bearing (black) or twin-bearing ewes (grey) and dashed lines represent upper and lower 95% confidence limits. Liveweight was corrected for cumulative wool weight and conceptus and adjusted for differences in ewe age. The data represents the average for ewes managed to achieve condition score 2 or 3 at Day 100 of pregnancy.

maintained liveweight throughout pregnancy. Staple strength at the WA site, where the ewes were shorn in autumn, was largely unaffected by liveweight change.

Treatment effect on subsequent reproductive rate

Reproductive rate in the year following the experiments was related to the nutritional treatment in late pregnancy and lactation in the previous year. On average, ewes at both sites from the lowest feed on offer treatment (800 kg DM/ha) were lighter ($P < 0.05$; see Fig. 2) at the subsequent joining and carried 20–30% fewer fetuses at scanning (Fig. 5) than those from the highest feed on offer treatment (3000 kg DM/ha), although this difference was not significant at the WA site in 2002. The number

Table 5. Coefficients (±s.e.) of restricted maximum likelihood linear models that predict ewe wool characteristics at the Victoria site in terms of ewe liveweight (LW) during different periods of pregnancy and lactation, rearing type [single (S), twin born reared as a single (TS) and twins (T)] and ewe age effects (fixed) after adjustment for blocking effects (random). As there were no differences between years the data is combined for 2001 and 2002

All coefficients were accepted into the model $P < 0.05$. n.s., not significant

Coefficient	Clean fleece weight (kg)	Mean fibre diameter (um)	Staple length (mm)	Staple strength (N/ktex)
Constant	1.62 ± 0.239[A]	16.70 ± 0.723[B]	86.1 ± 3.54[B]	29.8 ± 3.25[A]
Ewe LW change Day 0–100	0.071 ± 0.0059	0.097 ± 0.0145	0.655 ± 0.0841	0.490 ± 0.0855
Ewe LW change Day 100–lambing	0.065 ± 0.0051	0.083 ± 0.0123	0.604 ± 0.0715	–0.216 ± 0.0780
Ewe LW change lambing–weaning	0.040 ± 0.0047	0.052 ± 0.0120	0.189 ± 0.0696	n.s.
Ewe LW at joining	0.043 ± 0.0043	0.084 ± 0.0114	0.400 ± 0.0660	n.s.
Rearing type TS	–0.088 ± 0.0475	n.s.	n.s.	–2.09 ± 0.711
Rearing type T	0.124 ± 0.0458	n.s.	n.s.	–1.46 ± 0.674
Age 3.5 years	0.169 ± 0.0389	0.565 ± 0.1143	–2.41 ± 0.663	2.08 ± 0.555

[A]The clean fleece weight and staple strength constant is for rearing class S and ewe age 2.5 years.
[B]The fibre diameter and staple length constant is for ewes aged 2.5 years.

Table 6. Coefficients (±s.e.) of restricted maximum likelihood linear models that predict ewe wool characteristics at the Western Australia site in terms of ewe liveweight (LW) during different periods of pregnancy and lactation and ewe age effects (fixed) after adjustment for blocking effects (random). As there were no differences between years the data is combined for 2001 and 2002

All coefficients were accepted into the model $P < 0.05$. n.s., not significant

Coefficient	Clean fleece weight (kg)	Mean fibre diameter (um)	Staple length (mm)	Staple strength (N/ktex)
Constant	1.93 ± 0.246[A]	16.77 ± 0.713	74.1 ± 4.32[A]	37.5 ± 0.53
Ewe LW change 0–100	0.054 ± 0.0077	0.142 ± 0.0210	0.560 ± 0.0867	n.s.
Ewe LW change 100–lambing	0.053 ± 0.0074	0.096 ± 0.0125	0.515 ± 0.0884	n.s.
Ewe LW change lambing–weaning	0.046 ± 0.0048	0.106 ± 0.0211	0.294 ± 0.0531	n.s.
Ewe LW at joining	0.037 ± 0.0049	0.068 ± 0.0148	0.245 ± 0.0629	n.s.
Age 3.5 years	0.056 ± 0.0628	0.276 ± 0.1953	–3.04 ± 0.826	n.s.
Age 4.5 years	–0.177 ± 0.0750	0.652 ± 0.2330	–5.01 ± 0.983	n.s.
Age 5.5 years	–0.438 ± 0.0890	1.07 ± 0.277	–6.77 ± 1.175	n.s.

[A]The clean fleece weight, fibre diameter and staple length constant is for ewes aged 2.5 years.

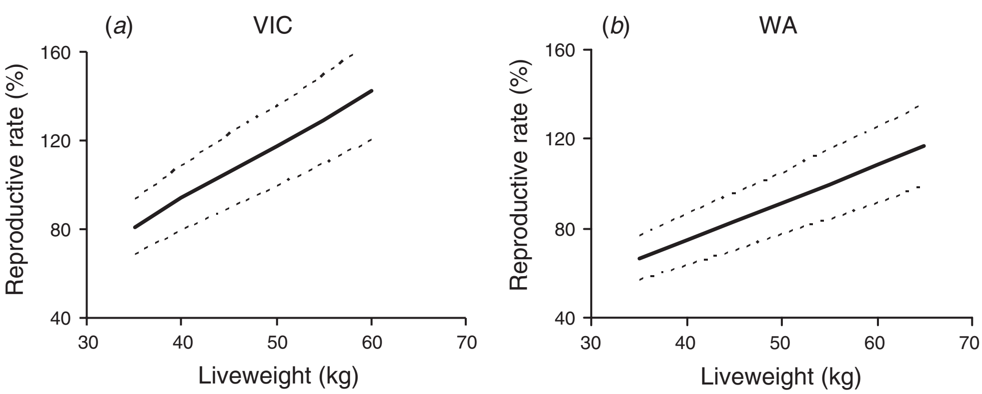

Fig. 5. Effect of the liveweight of ewes at their subsequent joining on reproductive rate (fetuses scanned per 100 ewe joined; %) at the Vic. (*a*; $Y = 2.4x - 3.3$) and WA site (*b*; $Y = 1.7x + 7.3$). The data is for 2001 and 2002 are combined and dashed lines represent upper and lower 95% confidence limits. Liveweight was corrected for cumulative wool weight and adjusted for differences in ewe age and rear rank during the previous reproductive cycle.

of fetuses scanned was related to liveweight of ewes at joining at both sites (Fig. 5). On average an additional 1 kg at joining resulted in an extra 2.4 and 1.7 lambs per 100 ewes at the Vic. and WA sites, respectively. The number of fetuses scanned was not significantly ($P > 0.05$) related to ewe liveweight change between weaning and joining.

Discussion

The clean fleece weight, fibre diameter and staple length of wool produced by individual Merino ewes was best predicted by their liveweight at joining and liveweight change during pregnancy and lactation. The similarity of the results across both years within sites and the small errors about the coefficients confirms the appropriateness and reliability of the relationships. Further confirmation of the value of the relationships is provided by the finding that the equations derived from the individual ewes in the present study can also be used to predict the wool production and quality of whole flocks (Behrendt *et al*. 2011). In a series of paddock-scale experiments conducted on farms across southern Australia, they found significant relationships between the liveweight of flocks in late pregnancy (Day ~140) and the wool they produced and these relationships were similar to the overall effects of changes in liveweight over pregnancy in the present study. Cannon (1967), Langlands (1969) and Allden (1979) also reported relationships between liveweight profiles of ewes and wool characteristics. The effects of liveweight change of ewes to mid pregnancy and during late pregnancy on clean fleece weight, fibre diameter and staple length were greater than the effects of liveweight at joining and liveweight change during lactation.The effects of poor nutrition up to mid pregnancy on these wool characteristics could be completely overcome by improved nutrition later in pregnancy. The fleece wool characteristics were less responsive to changes in liveweight during lactation than during pregnancy, which is consistent with the work of Masters *et al*. (1993). The relationships between the liveweight profile of ewes and their clean fleece weight, fibre diameter and staple length were consistent and therefore we accept our second hypothesis.

The staple strength of wool produced was related to the liveweight profile of individual ewes at the Vic. site. The impact of ewe liveweight change on staple strength was similar across years, further supporting the hypothesis, but the nature of the responses differed to the effects of liveweight change on clean fleece weight, fibre diameter and staple length. There was a positive relationship between liveweight change to mid pregnancy and staple strength whereas in late pregnancy this relationship with staple strength was negative. This difference was explained by the timing of the point of break which coincided with the end of the condition score treatments and allocation to feed on offer treatments at Day 100 of pregnancy. Ewes with greater liveweight gain to mid pregnancy had a higher minimum fibre diameter resulting in higher staple strength, but greater liveweight gain in late pregnancy increased along-fibre variation in diameter resulting in increased linear density and therefore a lower staple strength. Both lowering the minimum fibre diameter and increasing linear density are known to decrease staple strength (Thompson and Hynd 1998). At the WA site there was no treatment or liveweight change effects on staple strength. This was expected as the sheep were shorn in autumn, which coincided with the time of minimum fibre diameter along the staple.

Birth type and rear type had impacts on ewe liveweight, clean fleece weight and staple strength but not on fibre diameter or staple length. At the Vic. site, twin-bearing ewes gained less maternal weight during late pregnancy and lost more weight during lactation, resulting in lower liveweight at weaning and the following joining which is consistent with Lee and Atkins (1995). Similarly, ewes that reared twins grew slightly less wool that was of lower staple strength than those that reared singles and these differences were expected (Masters and Stewart 1990). As a result birth type and rear type of ewes did influence the ability to predict clean fleece weight and staple strength from ewe liveweight change. Therefore, it is important to consider birth and rear rank in the prediction, but their direct effects on clean fleece weight and staple strength are smaller than those due to changes in liveweight of the ewe.

The influence of food on offer on changes in ewe liveweight was different between years and sites and between late pregnancy and lactation supporting our first hypothesis that feed on offer has variable effects on liveweight profiles of individual ewes. Similar variations in the relationship between feed on offer and liveweight changes have been reported for dry sheep (Thompson *et al*. 1994, 1997; Hyder *et al*. 2002) indicating that a complex group of pasture and animal factors influence the relationship between feed on offer and liveweight change. Feed on offer treatments in late pregnancy and lactation also had variable effects on ewe clean fleece weight, fibre diameter and staple length. This variation in ewe liveweight and wool production responses to feed on offer indicates that managing ewe liveweight change itself will achieve more predictable outcomes than managing ewes using different levels of pastures alone. Nonetheless, feed on offer remains an important tool to assist in achieving ewe liveweight or condition score targets within site or year.

The reproductive rate (lambs scanned in utero per ewe joined) of individual Merino ewes increased with liveweight at mating and the responses were consistent across years for each site. The linear response is consistent with Lindsay *et al*. (1975) and Morley *et al*. (1978). The average increase in reproductive rate was about two extra fetuses per 100 ewes per kg of liveweight, which is at the high end but consistent with previous work (Kelly and Croker 1990). There was a significant impact of nutrition during the previous year on the subsequent reproductive rate but this effect was entirely explained by the liveweight achieved at mating rather than the liveweight change from weaning to mating, which is consistent with Gunn and Maxwell (1989). Hence, a higher liveweight at joining resulted in a predictable improvement in ewe reproductive rate and liveweight at mating was more important than the liveweight profile leading up to mating.

This paper has shown that ewe liveweight profile is consistently related to fleece characteristics and reproduction. These relationships could be used to predict changes in the wool characteristics of flocks in response to a given liveweight profile. This is supported by the series of paddock-scale experiments conducted on farms across southern Australia (Behrendt *et al*. 2011). This knowledge combined with the full range of impacts of ewe nutrition on ewe and progeny performance (Oldham *et al*. 2011; Thompson *et al*. 2011*a*, 2011*b*), has enabled the development of regionally specific management guidelines for reproducing Merino ewes (Young *et al*. 2011).

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