Final report

Refining body condition score for region, season, breed and responsiveness

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Abstract

Historical farm system simulation models have suggested that feeding ewes to attain body condition score (BCS) 3 throughout the reproduction cycle decreased profit, except when flocks were highly responsive to BCS (i.e.16% more lambs born at BCS 3) and when grain was cheap. Furthermore, little published information is available to examine the relationships between body condition score and reproduction outcomes when flocks are mated in different seasons, and in addition to this, little information for these relationships are available for composite or shedder sheep breeds.

A field study was undertaken that collected 30,030 adult ewe BCS and liveweight within a fortnight of the start of mating. At mid-pregnancy ultrasound pregnancy diagnosis was performed to collect pregnancy and litter size status from Composite (n=16), Maternal (n=14), Merino (n=23) or Shedder (n=5) flocks, including 29,125 complete ewe records. Sheep producers were recruited in NSW (n=44), Victoria (n=9) and South Australia (n=3). The flocks were mated in either spring, summer or autumn. Body condition score was assessed by a single, trained operator. The mean number of ewes in each flock was 514 and ranged from 350 to 1014 head.

The average fertility (pregnant ewes per ewe scanned) observed in the field study was 90.4%. Differences were present between breeds and seasons and due to body condition score, liveweight and the quadratic terms for body condition score and liveweight. The inclusion of quadratic terms for liveweight and body condition score improved the variation explained by the model for fertility and demonstrates curvilinearity. Terms describing the seasonal conditions during mating were also significant. When compared to Composite ewes, all breeds had lower fertility, which was the lowest in Shedding ewes, while Merino had higher overall fertility than Shedder and Maternal ewes. Ewes mated in autumn had the highest mean fertility, spring mated flocks the lowest mean fertility and summer mated flocks intermediate to these. Fertility was lowest when seasonal conditions during mating were described as *well below average*.

The average pregnancy scanning rate (fetuses per ewe scanned) was high at 150.1 ± 70.4%, with Composite ewes recording very high rates overall. Pregnancy scanning rate was improved by liveweight, body condition score, and varied between seasons and breed. When compared to Composite flocks, the scanning rate was lower in all other breeds, and was lowest in the Shedder flocks, with Merino second lowest and Maternal second highest. Flocks mated in autumn had the highest scanning rate, while summer mated flocks were the lowest. The number of rams per 100 ewes had a significant effect, where scanning rate decreased as ram per cent increased above 2%. The inclusion of quadratic terms for liveweight and body condition score improved the variation explained by the model for scanning rate, demonstrating curvilinearity.

The results from the field study were used to inform farm system modelling, using the Ausfarm package. Six locations across New South Wales (Bookham, Bungarby, Condobolin, Glen Innes, Narrandera and Trangie), one location in Victoria (Hamilton) and one in South Australia (Keith) were modelled and scenarios of high, average (base) and low rates of reproduction at BCS 3 were created. The reproduction rates were set at approximately ±20% of the breed mean. Overlayed complexity included season of mating (spring, summer, autumn), three breeds of sheep (Composite, Maternal, Merino) and three levels of grain price (high, $394/t; base, $315/t; and low $236/t). In total, 648 optimised scenarios were examined.

The results are written in a way to highlight the most or least profitable scenarios and their riskiness, but there is no focus on dollar terms. Riskiness was examined using conditional variation at risk (CVaR), which estimates a probabilistic average profit in the bottom 20% of years.

Detailed interpretation of the numerous model outcomes is provided separately, per location, enabling producers to find an environment, ewe breed, reproduction rate and grain price similar to their situation and judge the effects of altering some of those factors, in particular reproduction rate grain price and season of mating. This study is not intended to examine the profitability differences between breeds and its findings do no advocate one breed over another. The findings are a result of the parameters defined in the model. The modelling reveals the value of high reproduction versus lower reproduction, at three grain prices to examine the impacts of decision making on farm system profitability, across three seasons of mating.

Recommendations for more data-driven management of ewe flocks are made. Reproduction response curves are demonstrated for four breeds and three seasons of mating. The decreases observed in fertility and scanning rate in the heaviest liveweight and heaviest condition score ewes is an important observation. Sheep producers should continue to strive for BCS 3 and will observe higher fertility and scanning rate as ewes reach BCS 3.5. The farm system models did not test the profitability of feeding ewes to BCS 3.5 and this study cannot make any recommendations for approach to reproduction management.

Recommendations are made for the expansion of parameters available for modelling new breeds, such as composite and shedding/Hair breed sheep.

Executive summary

Background

Historical farm system simulation modelling has suggested that feeding ewes to attain body condition score (BCS) 3 throughout the reproduction cycle decreased profit, except when flocks were highly responsive to BCS (i.e. 16% more lambs born at BCS 3) and when grain is cheap. Furthermore, little published information is available to examine the relationships between body condition score and reproduction outcomes when flocks are mated in different seasons, and in addition to this, little information for these relationships are available for composite or shedder sheep breeds.

Therefore, this project had two focal points. First, to test the on-farm relationships with body condition score and liveweight with pregnancy scanning outcomes using different breeds and when mated in different seasons. The second was to identify the economic impacts of high reproduction rates and grain prices using farm system modelling to test this objective in different breeds and seasons of mating.

The target audience was sheep producers in southern Australia, in particular those that have completed the Lifetime Ewe Management training program and are adopting body condition scoring, individual animal identification and pregnancy scanning to drive the productivity and profitability of their flocks. This is the target audience because these producers have the skill, equipment and data to identify reproduction response curves within their own flock using data they create for their decision making.

The on-farm results will be used to refine our understanding of the relationships between reproduction outcomes (fertility and litter size) and pre-mating body condition score and liveweight. The farm system modelling results will be used to support producer decision-making when considering the effects on their farm when altering management to achieve higher reproduction rates, and the impact of grain price on profitability, or if choosing to mate their flock in a different season. The results are not intended to compare the profitability of different breeds or locations.

Objectives

The objective of the field study was to examine the relationships between pre-mating body condition score and liveweight with pregnancy status and litter size outcomes across four breeds (Composite, Maternal, Merino and Shedder) and three seasons of mating (spring, summer and autumn). In total, 58 flocks were sourced, yielding 30,030 ewes providing 29,125 individual pregnancy scanning records. The data successfully reveals reproductive response curves for each breed and season of mating.

The farm system modelling intended to model the impacts on profitability of three different reproduction rates in sheep breeds (Composite, Maternal and Merino) under three grain prices, when mated in each season (spring, summer and autumn). The farm system modelling was completed for 8 locations ins NSW, Vic and SA and successfully demonstrates the impacts on profitability.

Methodology

The field study exclusively collected adult ewe body condition score (BCS) and liveweight records within a fortnight of mating and pregnancy status and litter size records were collected by ultrasound scanning in mid pregnancy. Analysis of the field data was undertaken using generalised linear models fitting quadratic terms for liveweight and body condition score.

The farm system modelling was performed using Ausfarm, CSIRO developed software that is code driven, allowing more nuanced rules to reflect real world decision-making. Base models were validated against published records or with subject matter experts familiar with the location. All 648 scenarios were optimised for the highest profit while meeting groundcover and grain-feeding rules.

Results/key findings

On-farm monitoring of pregnancy rate and litter size demonstrate curved, rate-limiting relationships with both BCS and liveweight. The nature of the relationships differed between breeds and seasons of mating, indicating a biological optimum BCS around 3.5 and decreases in fertility and scanning rate in animals more forward in condition. Similarly, optimum liveweights were around 60-70 kg and decreases in pregnancy rate and litter size were observed in ewes heavier than this range.

The farm system modelling demonstrated increased profitability under high reproduction levels and decreases in profit with higher grain price. The riskiness of the systems tested are also defined in profit terms. Detailed results are provided per location as additional materials to this report.

Benefits to industry

Awareness of rate-limitations associated with BCS or liveweight beyond BCS 3.5 or 70 kg liveweight will help sheep producers understand the value in setting upper and lower BCS targets for pre-mating ewe management for their own flock. The results should also stimulate producers into testing the relationships within their own flock.

The riskiness of the farm systems modelled are defined in profit terms and allow producers to understand the profit implications of altering their farm systems to achieve higher or lower reproduction rates, or by changing the season of mating, or under higher grain price scenarios.

Future research and recommendations

Development of a Microsoft Excel software program to test response curves for individual producers would be helpful in establishing targets within a flock.

The fertility and scanning rate of shedder/Hair sheep was low and more research is needed for these breeds. Capturing data that fairly represents the breed requires investigations to occur within flock over multiple mating cycles, using multiple flocks located in high and low rainfall environments.

Modern Australian sheep breeds include mixed breed composite and shedding/Hair sheep and these genotypes are not truly available in the Grazplan farm system decision support software packages, (Grazfeed, GrassGro and Ausfarm). Future R&D is required to define parameter sets for these breeds to enable more accurate evaluation in modelling software.

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1. Background

Body condition score is a subjective assessment of body reserves, first described by Jefferies (1961). The loin was identified as the site for body condition scoring because it was the '*latest developing part of the growing animal, the last place to put on fat and the first to lose it'*. The research and adoption programmes; Lifetime Wool and Lifetime Ewe Management (LTEM), have successfully translated the importance of body condition score (BCS) to reproductive outcomes. Substantial increases in the number of producers using BCS and drafting ewes on the basis of BCS are demonstrated; so too producer attitudes towards targeted supplementary feeding, as a result of participation in the program (Trompf *et al.*, 2011). For example, producers completing the LTEM post-training surveys highly rated their belief that higher BCS led to higher conception rates, increasing from 3.25 out of 5 pre-training to 4.9 out of 5 post-training.

Converting the biological outcomes of improved BCS on reproductive output into economic impacts has been part of the extension strategy. Bio-economic optimisation of animal and pasture management across the whole farm indicates the optimal time of mating and from which industry extension messages are produced. Using GrassGro^{TM} (Moore *et al.* 1997), Graham and Hatcher (2006) showed for all simulations that the cost of supplementary feed required to meet fat score targets was the key driver of profit, highlighting the importance of meeting targets using pasture. Optimising farm management, with tools like GrassGro^{TM} or in particular the Model of an Integrated Dryland Agricultural System (MIDAS) (Kingwell and Pannell 1987), led to the Industry's LTEM extension package sensibly relying on their conclusions.

MIDAS is a deterministic, comparative static general equilibrium model and includes a powerful feed budgeting module, although unlike GrassGro^{TM}, variation in seasonal conditions from year to year is not explicitly included (Young *et al.*, 2010). The model calculates if the most profitable way to achieve the required nutrition for the flock is by adjusting stocking rate, grain feeding or grazing management (Young, 2007). Unfortunately, GrassGro^{TM} simulations (Phil Graham, *pers. comm.*) suggest that feeding ewe flocks to attain BCS 3 throughout the reproduction cycle can decrease profit by $15 to $55/Ha, except when flocks are highly responsive to BCS (i.e.,16% more lambs born at BCS 3) and when grain is cheap. When high reproduction at BCS 3 meets low grain price, profit increased by $5 to $45/Ha.

A limitation of the MIDAS and GrassGro^{TM} models is that sub-classes of the flock cannot be created; instead, all ewes are managed equally. It is possible that the same reproduction targets can be achieved through separation of cohorts and preferential treatment of the neediest ewes that are most likely to respond economically to improved nutritional status. For example, grain feeding costs could be decreased by up to 76% via segmentation (Jordan *et al.*, 2006). An alternative to MIDAS and GrassGro^{TM} is the more complex Ausfarm package, which enables the evaluation of sheep production systems that although widely used in practice, could not previously be simulated (Robertson and Friend, 2013; Robertson *et al.*, 2014).

An underlying assumption of improved ewe management to improve reproductive performance is a positive linear response between BCS and ewe fertility. Australian sites in the Lifetime Wool project averaged 22% more lambs scanned per ewe as BCS increased 1 score (Hatcher, 2005). However, Killeen (1967) suggested limiting returns as ewe condition increases. Kenyon *et al.* (2014) reflected upon this: '*it might be expected that as BCS increases, the relative gain in ovulation rate might also be reduced and that ewes of higher BCS will be less responsive to improved nutrition in comparison with ewes of low BCS*'.

Previously, Kenyon *et al.* (2004) found different ewe breeds have differing target BCS for reproduction outcomes, with some breeds not being required to have ewe BCS greater than 2, while other breeds have improved reproduction at BCS 3. Hatcher (2005) reported some NSW flocks of the Lifetime Wool project were not responsive to higher body condition, where groups differing by a full fat score did not differ substantially in scanning rate. Pregnancy scanning rate changed between FS 2 and FS 3 by -4% to +6%. This is not likely a feature of fat scoring, which some work suggests is similar to BCS (Shands *et al.* 2009), although others disagree with that contention (van Burgel *et al.* 2011). Nevertheless, measures of ewe nutritional state and the degree of fatness and tissue accumulation appear to vary in their relationship with reproduction outcomes.

Variation in reproductive rate also exists between bloodlines and strains; Mortimer and Atkins (1997) reported the range in lambs weaned per ewe mated was 0.24. Together these reinforce the notion that variation exists between flocks, but little is known about the extent of that variation and what it means for producers setting pre-joining BCS targets and the implication for their operations. In order to optimise nutritional strategies leading to increased ewe fertility and litter size, producers should know if their flock's fertility is more or less responsive to BCS (Hatcher *et al.*, 2007; Hatcher *et al.*, 2006). An insightful piece of evidence is reported by Kleemann and Walker (2005), showing two response curves for ovulation rate across a range of body condition scores and mated in either spring or summer: no correlation was observed in the October to December mated flocks (R^2=0.09); January to March mated flocks were much better (R^2=0.37).

Many producers may not operate according to their recommended optimum, as outlined in Table 1. A significant finding of a producer survey (Croker *et al.* 2009) was that at least 50% of sheep producers were mating their ewes in summer. Table 1 is taken from the LTEM website and indicates for a range of production zones the target BCS and optimal time of lambing to achieve maximum profit. Elsewhere, evidence from pregnancy scanner records from 2009 to 2018, containing 2,342,000 ewes (Refshauge, unpublished data) indicates 76% of producers in the cereal-sheep and high rainfall zones of NSW join their flocks in spring or summer; not the optimum time.

Table 1. Optimum BCS and lambing time for the stated production zones, including the economic model. Taken from http://www.lifetimewool.com.au/guidelines.aspx (accessed 03/10/2018)

Production zone	**Optimum joining BCS**	**Optimum joining time** *(adapted from lambing time listed on website)*	**Model**
NSW Northern Tablelands	3.5	Autumn	Not listed
NSW High rainfall	3.0	Autumn	Western Victoria MIDAS
NSW Southern slopes	2.6	Late Summer/ Autumn	Wagga Wagga MIDAS
Vic Central northern	2.6	Late Summer/ Autumn	Little River MIDAS
Vic Cereal Sheep	2.6	Early Summer	Not listed
Vic High rainfall	3.0	Autumn	Western Victoria MIDAS
Tas High rainfall	3.0	Autumn	Western Victoria MIDAS
SA Cereal Sheep	2.6	Early Summer	Eastern Wheatbelt MIDAS

Production zone	Optimum joining BCS	Optimum joining time *(adapted from lambing time listed on website)*	Model
SA High rainfall	3.0	Autumn	Western Victoria MIDAS
WA Cereal Sheep	2.6	Early Summer	Eastern Wheatbelt MIDAS
WA Medium rainfall	3.0	Late Summer	Great Southern MIDAS

Furthermore, an important question that has not been examined is, if your flock has low reproduction responsiveness, what is your target BCS? Therefore, the gaps in the knowledge base this project aimed to address include:

- Do flocks vary in their response to higher BCS?
- What are the effects of season on scanning rate responsiveness to mating BCS?
- Are the relationships different between breeds?
- When using the powerful bio-economic modelling Ausfarm software, what impact on profit is observed when sheep are fed for BCS 3 and when differences exist in scanning rates at a range of condition scores?

The results of this work will support the refinement, as necessary, to target BCS for a range of seasons and breeds, and to provide support to industry recommendations about the value of reproduction to sheep business profitability.

2. Objectives

2.1 Ausfarm modelling

The modelling will produce gross margin results for reproduction response rate to higher body condition score (BCS) and test a number of variables such as breed, season of mating within each of the regions and grain price. The regions examined will include:

- Central Northern NSW (summer dominant, Glen Innes)
- Southern Tablelands (winter dominant, Bookham)
- Monaro (winter dominant, Bungarby)
- Riverina (winter dominant, Narrandera)
- Central Western NSW (non-seasonal, Condobolin & Trangie)
- Keith, SA (winter dominant)
- Hamilton, VIC (winter dominant)

Eight locations were modelled but did not include a rangeland environment. The rangeland environments due to vegetation type and structure are difficult to accurately model, at this time. Farm system modelling using Ausfarm was undertaken by Charles Sturt University PhD postgraduate candidate, Ms Amy Bates, with the experienced support of their supervisors (Dr Shawn McGrath, Dr Susan Robertson, Professor Bruce Allworth and Dr Gordon Refshauge).

2.2 On-farm assessments of ewe BCS and analyse their relationship with pregnancy scanning results.

The objective was to collect data from commercial flocks incorporating the intended variation in breed, season of joining and region to obtain 49,500 individual ewe liveweight and condition score records before mating. Consultants, researchers, Breed Societies, stud breeders and personal relationships were pursued to seek out sheep producers with the breeds of interest. In total, 30,030 ewes were assessed from 59 flocks, falling short of the objective. Engagement from producers with shedding hair sheep was difficult. Furthermore, the COVID-19 pandemic added further difficulty and risk to achieving the objective with opportunities missed due to border closures, stay at home orders and the risk of 14-day isolation requirements.
A key point of difference to previous work was that one person, trained in condition scoring, made all of the ewe BCS assessments.

2.3 Collated on-farm data on the number of lambs scanned and utilised Ausfarm modelling to incorporate this information into an analysis on the range of reproduction responses observed and formatted the results for incorporation into adoption packages.

The on-farm data collected from the 30,030 ewes (59 flocks) was incorporated into the Ausfarm reproduction and liveweight assumptions. Statistical analyses for the relationships between BCS or liveweight and fertility or pregnancy scanning rate have identified flock pre-mating targets for adult ewes. Several analytical approaches have been undertaken and agreement between findings is reached. Preparation of the key new information into existing adoption packages has commenced.

2.4 Submitted a final report to MLA detailing the range of reproduction responses observed and the implications for optimising BCS by season, breed and region.

Completed

2.5 A secondary output will be to have successfully submitted three journal articles to Animal Production Science on the trials and outcomes of the project.

Four research papers are planned for publication. At the time of writing, one paper had been submitted (to Animals, not APS).

3. Field Data

3.1 Methodology

Sheep producers were engaged either directly via existing relationships, or largely via networks with consultants or breed societies. In total 58 flocks (individual mob of ewes) were engaged from NSW (n=44), Victoria (n=9) and South Australia (n=3), where two flocks were different breeds on the same farm. These flocks were Composite (n=16), Maternal (n=14), Merino (n=23) or Shedder (n=5). The mob sizes ranged from 350 to 1014 ewes, averaged 514 adults and each was managed as a single cohort within farm.

A single, trained assessor undertook all body condition scoring. If not already, all ewes were identified with electronic identification (EID) tags and were weighed, and condition scored. Within two weeks from the commencement of mating, all ewes were weighed to 0.5 kg using calibrated load bars and a portable weigh crate. Ewes were condition scored to 0.25 units. On one farm, liveweights were not collected because of a failure of one load bar.

Producers were asked to provide additional information about the seasonal conditions, dates for mating and the ram percentage. Seasonal conditions were subjectively assessed by the producer to be one of Well above average, Above average, Average, Below average and Well below average. At approximately 87 days after the introduction of the rams, ultrasound pregnancy diagnosis was undertaken to identify pregnancy status and multiples. One site was not scanned for multiples because access to the stock yards was not possible due to above average rainfalls. Only pregnancy status was collected at that site. One other site was scanned for multiples but at lamb marking concerns were raised about the accuracy of the scanning, with very high marking rates in the single-scanned ewes. Only pregnancy status was used at that site as well.

Fertility data (ewe pregnant or not) was analysed using logistic regression in generalised linear models fitting a binomial distribution, with terms for season, breed, producer-assessed seasonal conditions during mating, ram percentage, liveweight and body condition score. Pregnancy scanning data (number of fetuses, 0, 1, 2, 3) was analysed using generalised linear mixed models with fixed effects for season, breed, producer-assessed seasonal conditions during mating, ram percentage, liveweight and body condition score and fitting a Poisson distribution. Site was included as a random term.

To test for curvilinearity, separate analyses were performed including quadratic terms for liveweight and body condition score. A full base model (model 1) was defined without quadratic terms, and a second model was defined that included the quadratic terms (model 2). The adjusted R^2 for each model was examined as was the average information criterion (AIC). A subsequent analysis of variance compared both models, which for all breeds showed the models significantly improved when the quadratic terms were included. Including the quadratic terms resulted in higher adjusted R^2, lower AIC and hence, are the models reported in the results. Differences were considered statistically significant when $P < 0.05$.

A trivariate analysis was used to investigate the co-relationship between weight and body condition score (BCS) for fertility and litter size. All statistical analyses were conducted with R version 4.0.5 statistical software (R Core Team, 2021)). The data was divided into eleven groups based on the variety of ewe and seasons for further analysis (Autumn Composite, Autumn Maternal, Autumn Merino, Autumn Shedder, Spring Composite, Spring Maternal, Spring Merino, Spring Shedder, Summer Composite, Summer Maternal, Summer Merino).

To assess the presence / absences of fertility of ewes, the lme4 package (Bates, et al. 2015) in the R statistical software was used to fit a generalized linear mixed-effects model (GLMM) with the binomial family using logit link function. Since we have three levels of foetuses' categories (one foetus, two foetuses and three or more foetuses), which are somewhat ordered categories. Hence the ordinal package (Christensen, 2019) in R was employed for fitting a cumulative link with ordinal mixed-effects model. Weight and BCS were used as fixed effects and their interaction was included in the model. To account for flock variation within each group, random intercepts were identified for each flock. The most suitable model was selected after examining the likelihood ratio test for random effects and Wald test for fixed effects. Statistical significance was defined as P < 0.05.

3.2 Results

3.2.1 Summary statistics

The number of flocks engaged in the study is reported in Table 8, which is supported by the report for the number of ewes in these breed and season combinations in Table 9.

A wide range of liveweight (Fig. 1) and body condition score (Fig. 2) data was captured in the study, and both were well distributed. The body condition score histogram is slightly left-skewed, with fewer Score 1 category ewes detected.

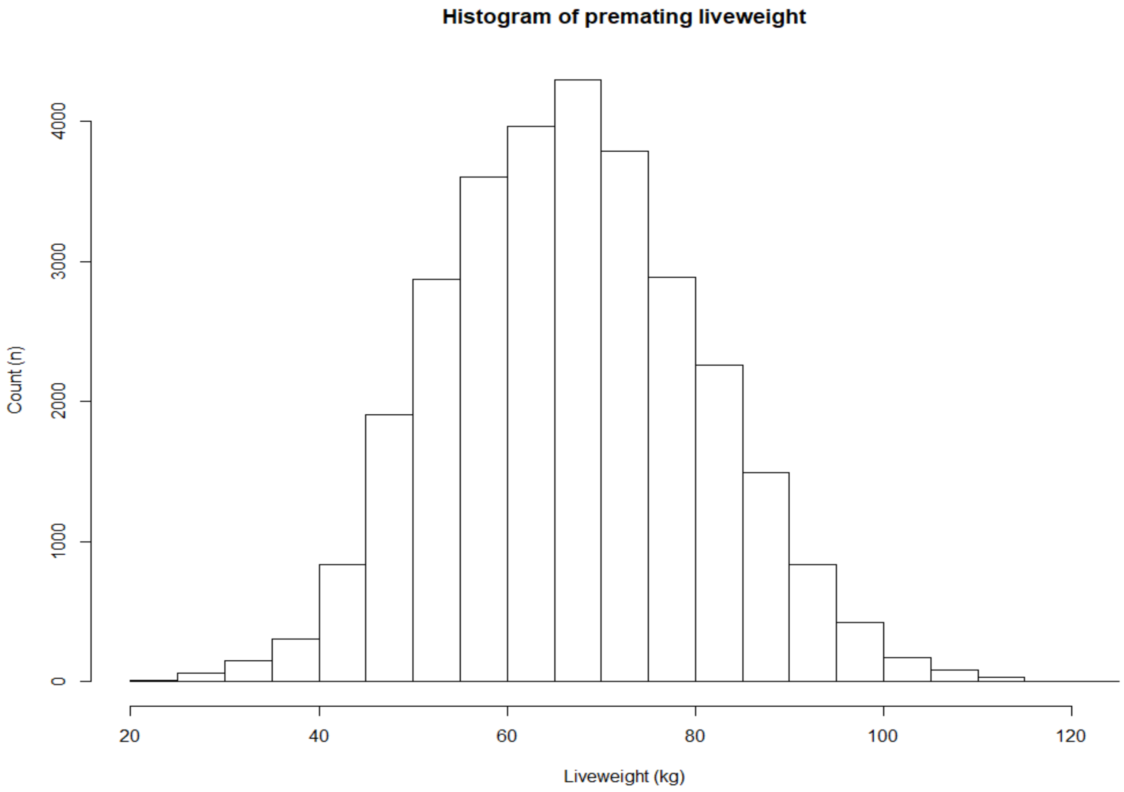

Fig 1. Histogram for ewe liveweight (kg) recorded before mating.

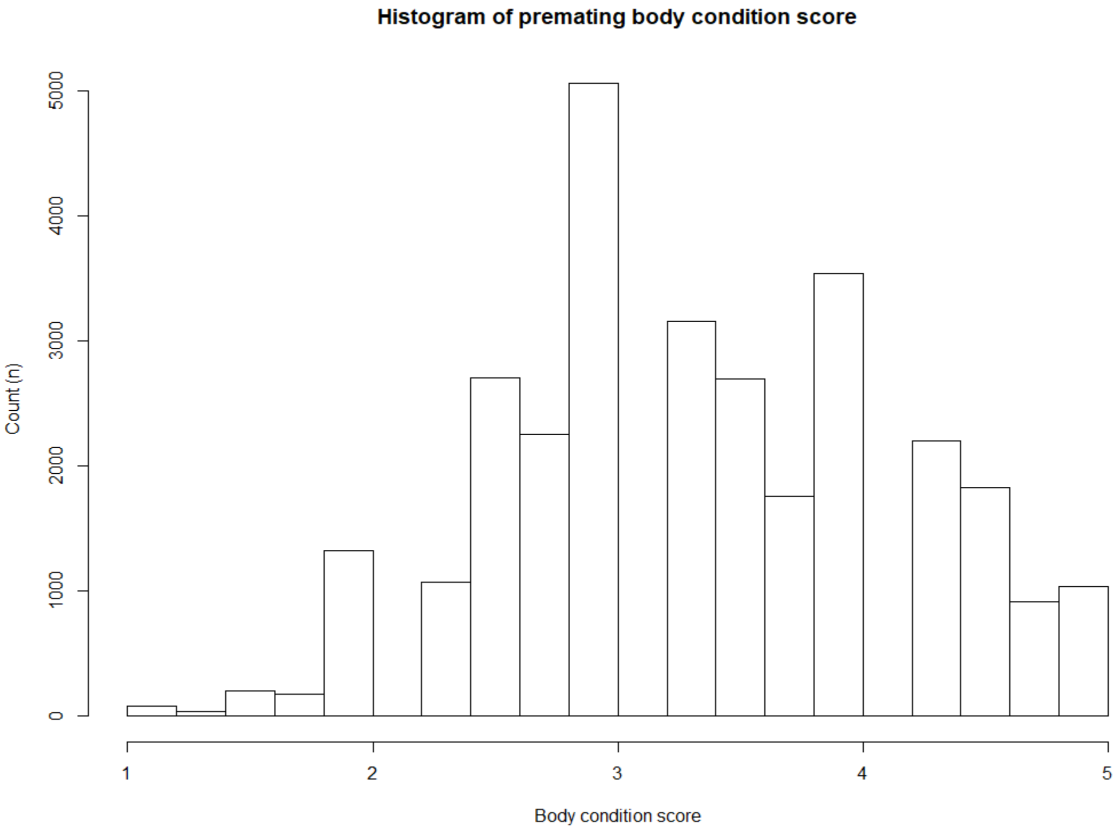

Figure 2. Histogram of body condition score.

Table 8. Number of flocks co-operating with the field study, for each breed and the season of mating.

Season	Composite	Maternal	Merino	Shedder	Total
Autumn	7	4	8	3	21
Spring	1	2	7	2	12
Summer	8	8	8		25
Grand Total	**16**	**14**	**23**	**5**	**58**

Table 9. Number of ewes tagged, weighed and condition scored pre-mating, for each breed and the season of mating.

Season	Composite	Maternal	Merino	Shedder	Total
Autumn	4401	1892	4230	1465	11988
Spring	458	979	3393	998	5828
Summer	4119	3959	4136		12214
Grand Total	**8978**	**7806**	**11759**	**2463**	**30063**

Mean pregnancy scanning rate was high at 150.1 ± 70.4%, with Composite ewes recording very high rates overall (Table 10). The scanning rate for the Shedder ewes should be considered to be low, given the result for Merino ewes. Pregnancy scanning rate was improved by liveweight (P<0.001), body condition score (P<0.001), season (P<0.01) and breed (P<0.05). Pregnancy scanning rate increased 1.3 ± 0.5% per kg liveweight and 17 ± 9 % per unit BCS.

3.2.2 Fertility

The mean fertility observed in the present study was 90.4%. Table 10 presents the means for each breed. Mean fertility differed between breeds (P<0.001) and seasons (P<0.001) and was also influenced by body condition score (P<0.001), liveweight (P<0.001) and the quadratic terms for body condition score and liveweight (P<0.001). The inclusion of the quadratic terms for liveweight and body condition score improved the variation explained by the model for fertility, evidenced by a lower average information criterion (base model AIC = 17158, quadratic model = 17010). Terms describing the seasonal conditions during mating were also significant (P<0.01). When compared to Composite ewes, all breeds had lower fertility, which was the lowest in Shedding ewes, while Merino had higher overall fertility than Shedder and Maternal ewes. Ewes mated in autumn had the highest mean fertility, with spring mated flocks the lowest mean fertility and summer mated flocks intermediate to these. Fertility was lowest when seasonal conditions during mating were described as *well below average*.

3.2.2.1 Body condition score

As body condition score increased, fertility also increased, although some impairment was observed in high BCS ewes. Fig 3 demonstrates the interactions between season and condition score for fertility within each breed type.

Fertility was decreasing in heavier conditioned Composite ewes when mated in spring and summer, while slightly increasing in autumn mated flocks. With only one spring-mated Composite flock, caution has to be advised around interpretation of that result, not just because the flock is singular for that breed x season, but also because the producer used Regulin to ensure pregnancy rates for their system. The shading around the line in Fig 3 is the standard error and suggests great variability after BCS 3.5. In terms of management decision making, it appears there is little to be gained by increasing body condition score in composite flocks beyond BCS 3.5. Three of the 16 Composite flocks were multi-meat bloodlines that contain fecundity genes.

In Maternal flocks, fertility increased sharply as condition score improved for flocks mated in summer and autumn but declines were apparent in forward score ewes (i.e. BCS ≥4.0). In spring-mated flocks fertility improved moderately to BCS 3 and declined after BCS 3.5. There were two spring-mated Maternal flocks and neither used Regulin. Some caution is advised when interpreting the trend for decreasing fertility in forward store condition spring-mated ewes, but the standard error shading in Fig 3 suggests sufficient numbers of ewes across this range, which increases confidence in this result. The increases in fertility as condition score increased in summer- and autumn-mated flocks is a good finding. The fitted polynomial regression lines indicate limiting returns in all Maternal flocks with BCS >3.5 and the standard errors for light condition ewes indicates large variability in fertility in lean ewes.

In Merino flocks, fertility differed between each season of mating; being highest in autumn-mated flocks. Fertility improved in all seasons as ewe body condition increased from lean to adequate condition (i.e. BCS 3.0). In spring- and autumn-mated flocks, fertility declined after BCS 3.5 (Fig 3). The standard error around the Merino results are small when compared to the other breeds and gives confidence in the Merino findings across the range of condition scores observed. Very few ewes in the study were BCS 1, yet the fertility for all ewes BCS <2 remained surprisingly high for their leanness, particularly in summer- and autumn-mated flocks. The fitted polynomial regression lines also indicate limiting fertility rates in ewes BCS >3.5. The greatest improvements in fertility occur between BCS 1 and 3 in spring-mated flocks.

In the Shedding flocks, there were no summer-mated flocks engaged in the study, with two spring- and three autumn-mated flocks. Despite this, the relationship between body condition score were the same for both seasons of mating, with substantial increases in fertility as condition score increased (Fig 3). Limited improvements occurred in ewes BCS >4 in autumn-mated flocks. The standard errors are large in lean ewes, indicating fewer numbers.

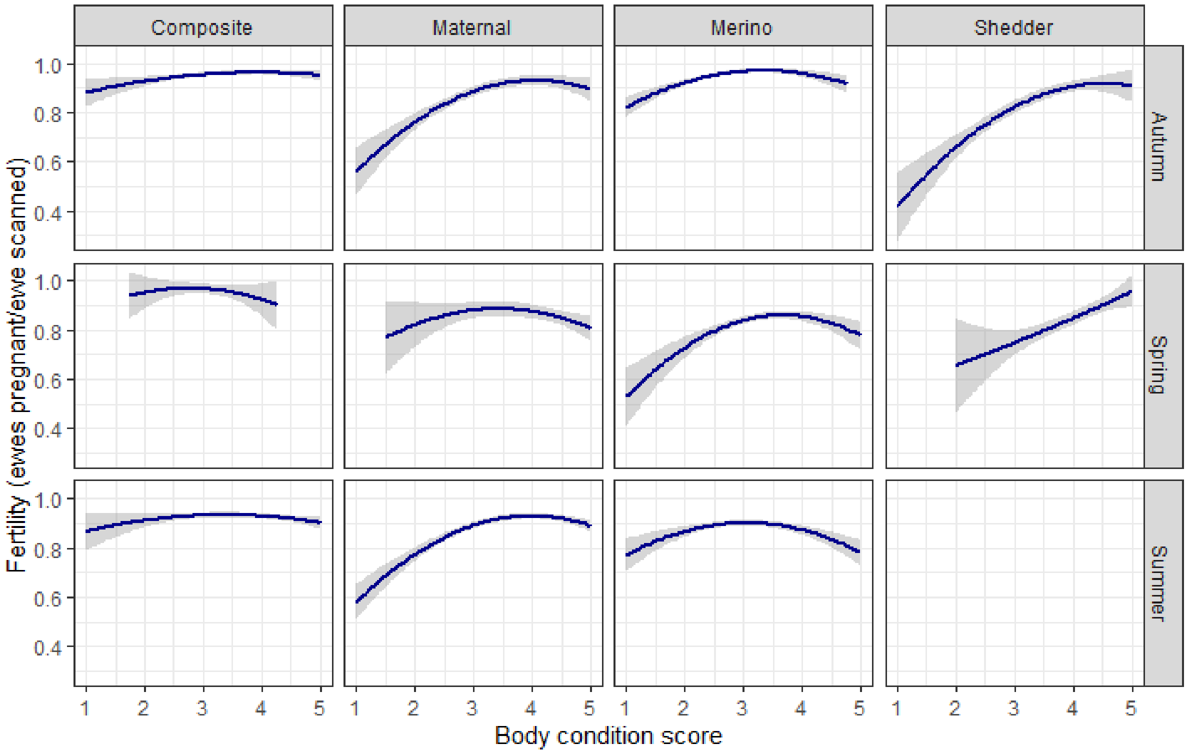

Figure 3. Plots reporting fertility (pregnancy rate) and body condition score for each breed with polynomial regression lines fitted for each season. Shading indicates standard error.

3.2.2.2 Liveweight

Relationships between each breed and within season are presented in Fig 4.

In Composite flocks, fertility increased in lighter ewes to about 60 kg, for all seasons of mating. As liveweight increased beyond 60 kg, there were clear reductions in fertility. Figure 4 demonstrates clear curvilinear effects of weight. Caution is advised when interpreting the spring-mated flock because there was only one flock, which was treated with Regulin® and were a flock containing fecundity genes.

In Maternal flocks, increased in fertility were observed through to a peak around 75 kg, with decreasing fertility thereafter. Quite rapid reductions in fertility were observed in autumn-mated flocks. High standard errors are observed at the weight extremes in the spring-mated flocks, indicating lower ewe numbers.

In Merino flocks, gains in fertility were observed as ewes increased in weight to 70 kg, with sharp decreases occurring after that weight in spring- and autumn-mated flocks. Summer mated flocks exhibit a curvilinear response rate, but which is reasonably flat.

The two seasons available for the Shedder flocks also indicate limiting rates of fertility as weight increased. The spring-mated flocks had quite sharp increases in fertility as liveweight increased to about 85 kg, with equally rapid decreases thereafter. For the autumn-mated flocks, the decreases in fertility were slight in ewes heavier than 75 kg.

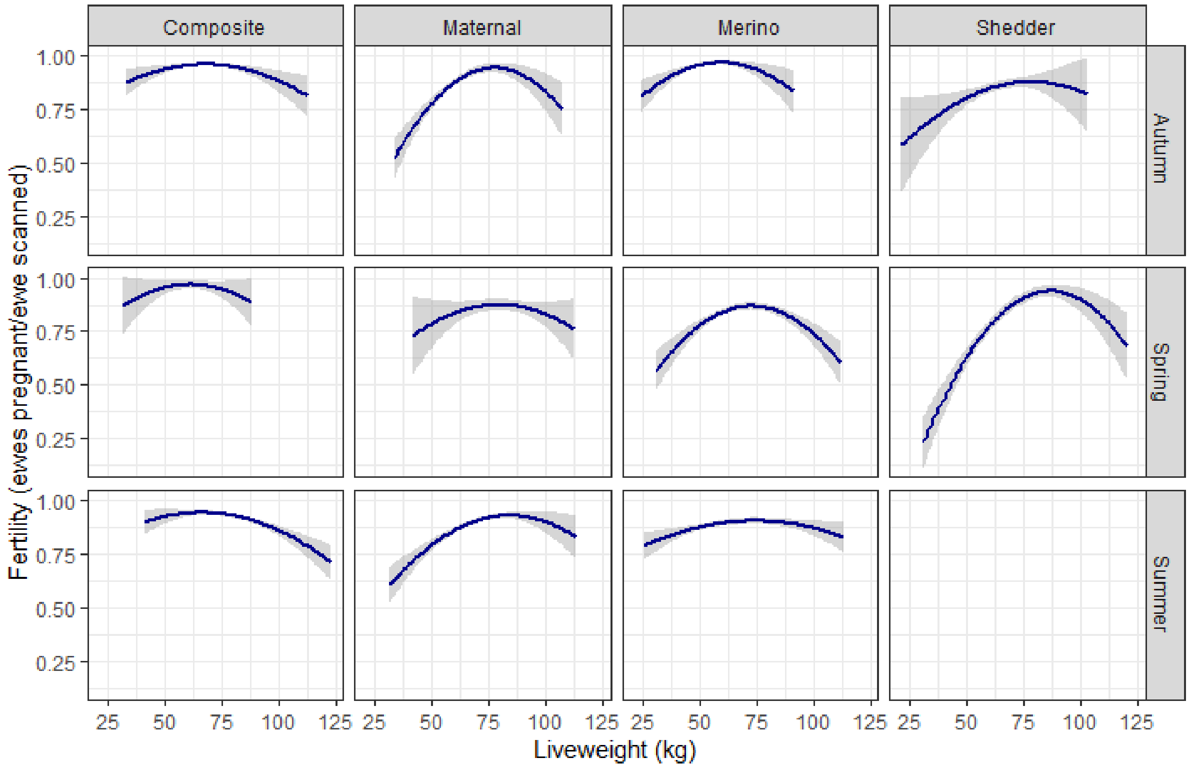

Figure 4. Plots reporting fertility (pregnancy rate) and liveweight (kg) for each breed with polynomial regression lines fitted for each season. Shading indicates standard error.

3.2.3 Pregnancy scanning rate (% fetuses/per ewe scanned)

Mean pregnancy scanning rate was high at 150.1 ± 70.4%, with Composite ewes recording very high rates overall (Table 10). Pregnancy scanning rate was improved by liveweight (P<0.001), body condition score (P<0.001), season (P<0.001) and breed (P<0.001). When compared to Composite flocks, the scanning rate was lower in all other breeds, and was lowest in the Shedder flocks, with Merino second lowest and Maternal second highest (P<0.001). Flocks mated in autumn had the highest scanning rate, while summer mated flocks were the lowest (P<0.001). The number of rams per 100 ewes had a significant effect (P<0.01), where scanning rate decreased as ram per cent increased. The inclusion of quadratic terms for liveweight (P<0.001) and body condition score (P<0.001) were significant and improved the model. The average information criterion improved between the base model (AIC = 69588) and the quadratic model (AIC = 69490). Pregnancy scanning rate increased 1.3 ± 0.5% per kg liveweight and 17 ± 9 % per unit BCS.

Table 10. The number of ewes pregnancy scanned for litter size in each breed type and the mean pregnancy scanning rate.

Litter size	Composite	Maternal	Merino	Shedder	Total
0	491	721	1195	366	2773
1	1628	1787	5333	934	9682
2	5043	3504	4794	1104	14445
3	895	89	22	48	1054
4	90				90
5	1				1
Total	**8148**	**6101**	**11344**	**2452**	**28045**
Fertility	94.0%	88.2%	89.5%	85.1%	90.1%
Mean scan rate	181.2%	148.5%	132.1%	134.0%	150.1%

Significant two-way interactions were observed for liveweight and body condition score (P<0.001), liveweight and season (P<0.001), liveweight and breed (P<0.01), body condition score and season (P<0.01) and body condition score and breed (P<0.01), while the interaction of breed and season tended toward significance (P=0.057). Site explained 9.9% of the residual variance in the model.

3.2.3.1 Body condition score

Pregnancy scanning rate increased gradually in Composite ewes (Fig 5) as body condition score increased. There were limiting returns in spring-mated composites, although caution is advised when considering the spring-mated Composite flock because that was the only flock mated in spring and used Regulin. In autumn- and summer-mated flocks there was very little response as body condition increased from lean to fat but gains were limiting in autumn, and in summer there were decreases after BCS 3.5.

In Maternal flocks, there were small differences observed between seasons, with the highest rates observed for autumn mated flocks (Fig 5). Importantly, pregnancy scanning rate increased between BCS 1.5 and 3.5. Spring-mated Maternal ewes had decreases in fertility as BCS increased beyond 3.5, whereas in autumn- and summer-mated flocks fertility continued to increase to about BCS 4.0 but decreased after that score.

In Merino flocks, autumn-mated flocks had the highest scanning rate, and all flocks an improved scanning rate as condition score increased from BCS 2 to 3.5 (Fig 5). Scanning rate continued to increase in autumn-mated ewes after BCS 3.5 but not after BCS 4. In spring-mated ewes, scanning rate decreased after BCS 3.75 and in summer-mated ewes after BCS 3.0.

In Shedder flocks, autumn mated ewes had higher scanning rates than spring-mated ewes (Fig 5). The spring-mated flocks have a large standard error at lower condition, which reflects ewe numbers. The polynomial regression line indicates limiting fertility as BCS increases in spring-mated Shedders but with gradually decreases in the slope of the line as BCS approached BCS 5 score . In autumn-mated ewes, scanning rate increased to BCS 4 and become limiting thereafter.

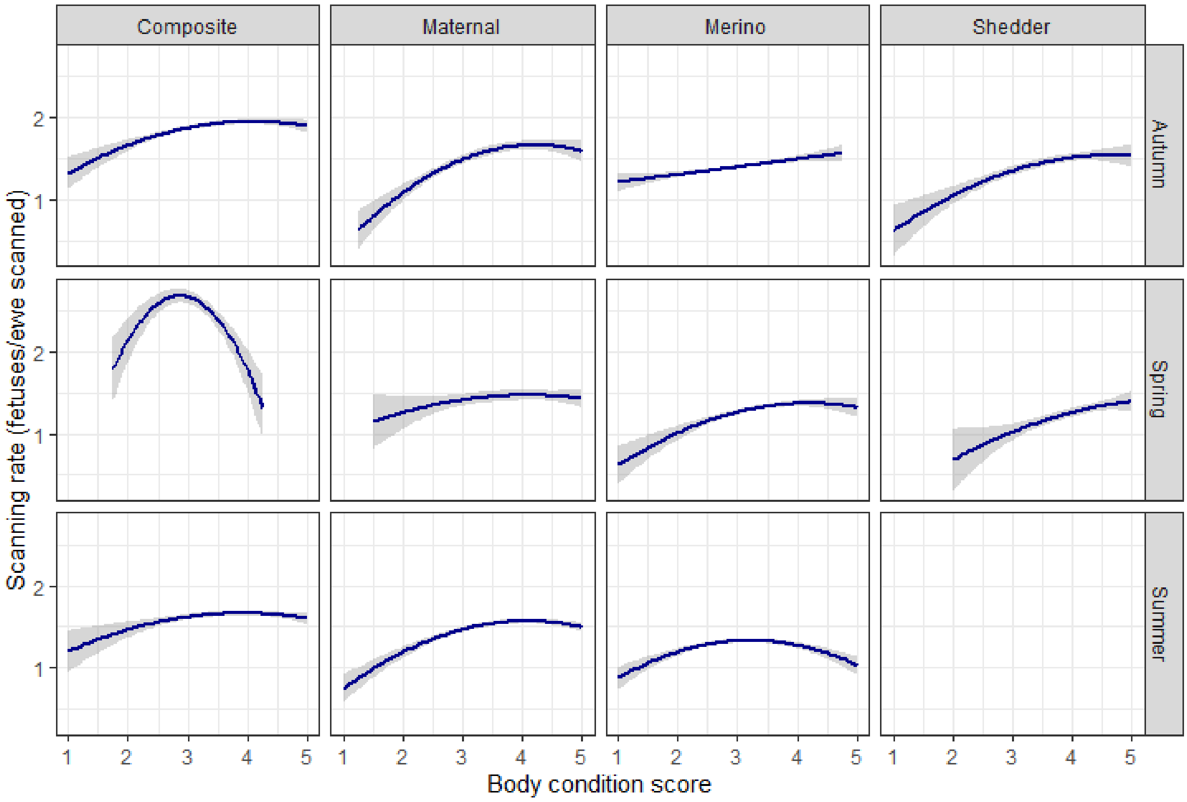

Figure 5. Pregnancy scanning rate (fetuses per ewe scanned) and body condition score reported for each breed with a polynomial regression line fitted for each season of mating. Shading indicates standard error.

3.2.3.2 Liveweight

Scanning rates in Composite ewes (Fig 6) are higher in autumn-mated flocks than summer-mated flocks. Scanning rate appears to decline to about 80 kg in autumn-mated flocks and slightly improves after that weight. The spring-mated flock used Regulin ™ and caution is advised in interpretation of the relationship with liveweight. In summer-mated flocks, improvements in scanning rate occur to 75 kg.

In Maternal ewes, scanning rate was higher as weight increased to about 80 kg, although in autumn, the peak scanning rate occurred at a lighter weight. All flocks exhibit curvilinear response rates as the ewes become too heavy, but the decreases are relatively minor in the spring- and summer-mated flocks (Fig 6).

In Merino ewes, lighter ewes were located in NSW tablelands environments, were generally super-fine wool types that typically have less selection pressure for reproduction, whereas the heavier Merino ewes were more likely to be dual-purpose type of breeding objectives with more emphasis on reproduction and carcase attributes. The relationship between scanning rate and liveweight exhibits limiting returns after to 75 kg in spring. However, summer-mated ewes responded to higher liveweights gradually (Fig 6). In comparison, autumn-mated ewes improved markedly as weight increased, without any apparent check, limiting in the rate of increase after 75 kg.

In Shedder ewes, the relationship between liveweight and scanning rate were similar for each season of mating (Fig 6). Scanning rate increases from to 80 kg ewes in autumn-mated flocks, and between to 100 kg in spring-mated flocks. Improvements in scanning rate are questionable in weights greater than those ranges.

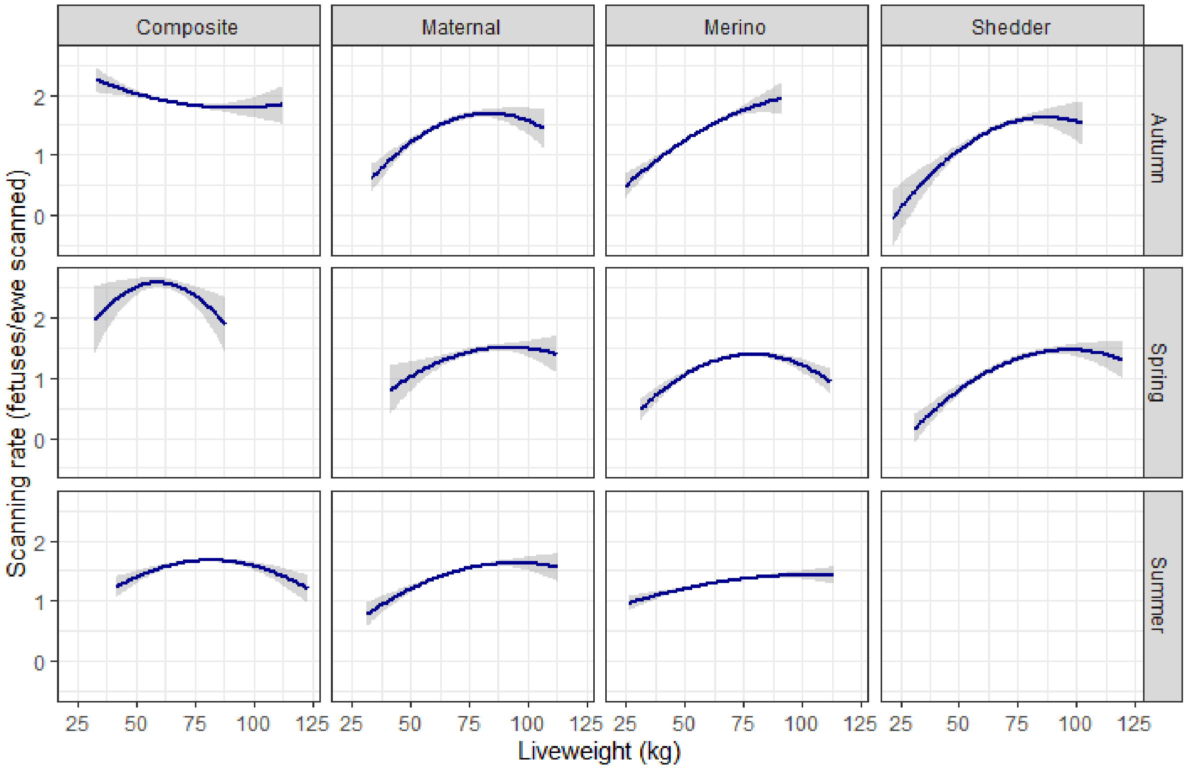

Figure 6. Pregnancy scanning rate (fetuses per ewe scanned) and liveweight (kg) reported for each breed with a polynomial regression line fitted for each season of mating. Shading indicates standard error.

Analysis presented in milestone reports demonstrated significant non-linear relationships between fertility and litter size with liveweight and body condition score. The following analysis uses pairwise comparisons to identify where the differences in fertility or litter size can be found between the body condition score or liveweights. The field data for liveweight and BCS were converted to factors for this analysis, enabling the pairwise comparisons. Analysis was performed using R (Ver 4.1.1, R Core Team 2021) and the emmeans package (Ver 1.7.4-1, Length et al., 2022), through which pairwise comparisons were made to determine the statistically significant differences.

Liveweight was categorised into groups largely consisting of 10 kg classes (Table 11). A histogram is provided (Fig 7) for the distribution of liveweight, and for the categories created in the factorisation of liveweight (Fig 8).

Table 11. Mean liveweight for the groups of liveweight classes created when factorising liveweight for pairwise comparison.

Category	Range	Average weight (kg)	Count
≤ 50	21.5 – 50.0	45.8	2728
60	50.5 – 60.0	55.7	6335
70	60.5 – 70.0	65.4	8239
80	70.5 – 80.0	74.9	6663
90 +	80.5 – 123	88.0	5305

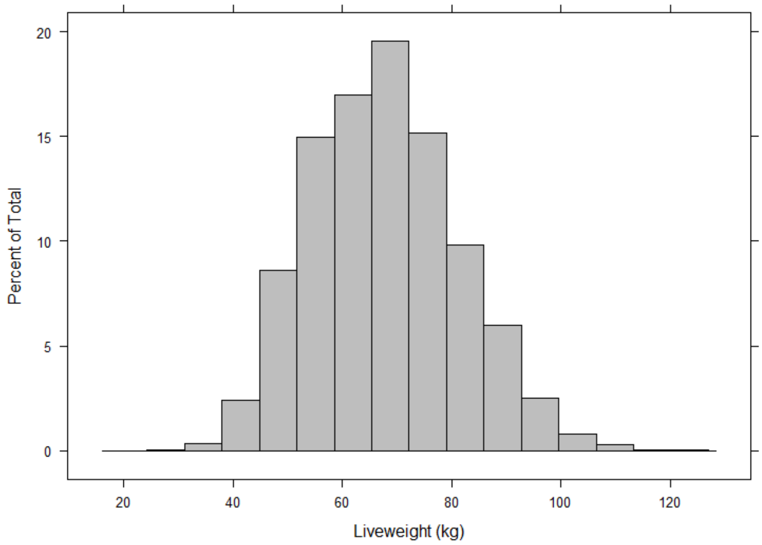

Figure 8. Liveweight histogram of raw data for all ewes

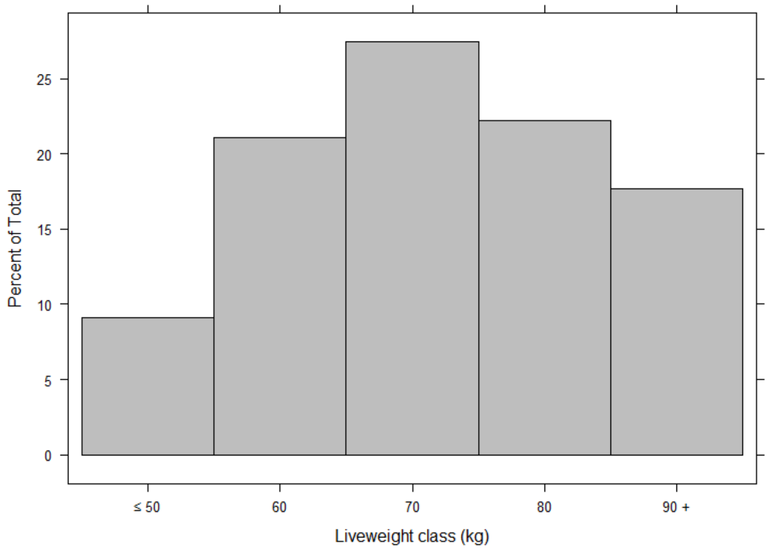

Figure 8. Histogram for liveweight categories created

Similar categorisation was performed for the body condition score to minimise the number of pairwise comparisons and increase the number of animals falling into each possible combination for BCS, breed and season. The distribution of animals into the categories is relatively uniform (Table 12). The distribution for the continuously variable raw data BCS (Fig. 9) and the distribution following categorisation (Fig 10.) and these suggest sufficient ewe numbers for each class.

Table 12. The number of ewes in each body condition score (BCS) class and the mean score.

Category	BCS	Count
< 2	1.49	498
2.0 - 2.5	2.32	5095
2.75 - 3.0	2.92	7307
3.25 - 3.5	3.37	5852
3.75 - 4.0	3.92	5297
4.25 - 4.5	4.36	4027
4.5 +	4.88	1954

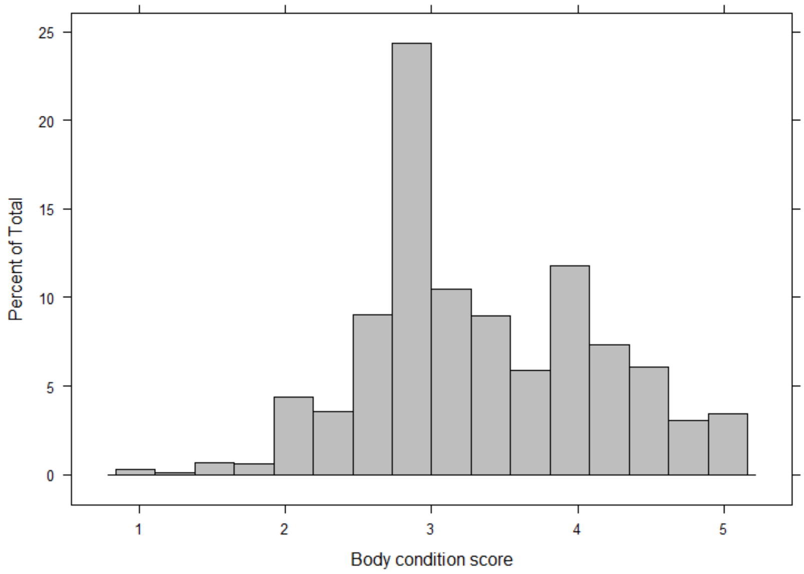

Figure 9. Body condition score histogram of raw data for all ewes.

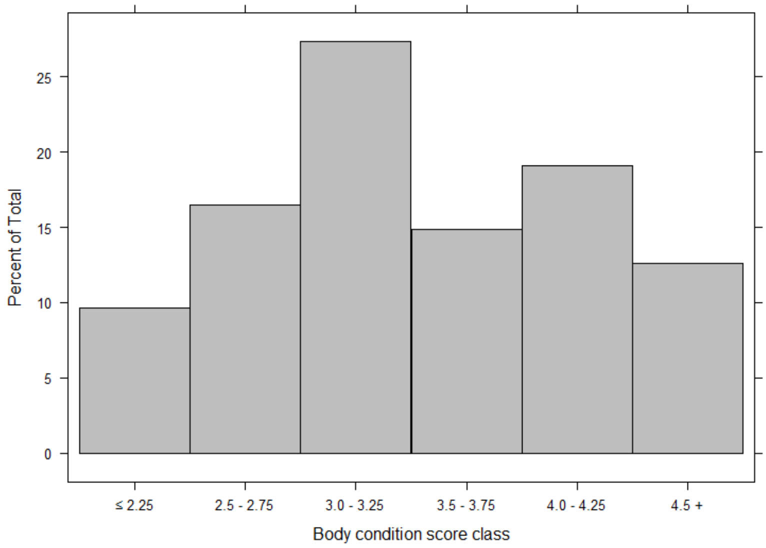

Figure 10. Distribution of body condition score as categories.

Pairwise comparisons - Fertility

3.2.3.3 Breed x Liveweight

Fertility was lower in Composite ewes in the 90+ kg class, while there was no difference in fertility between the 60, 70 and 80 kg classes (Fig. 11). The lightest class of ewes had high standard errors. In Maternal ewes, higher fertility was observed as the weight class increased from ≤50 kg to 70 kg, but there was no difference between the 70, 80 and 90+ kg classes. Fertility in Merino ewes increased from ≤50 kg to 60 kg where it was at its highest level. While there was no difference in fertility between 60 and 70 kg ewes, there was a decrease in ewes 80 and 90+ kg. In Shedder ewes there was a significant increase in fertility as the weight class increased to 70 kg, but there was no increase in heavier ewes.

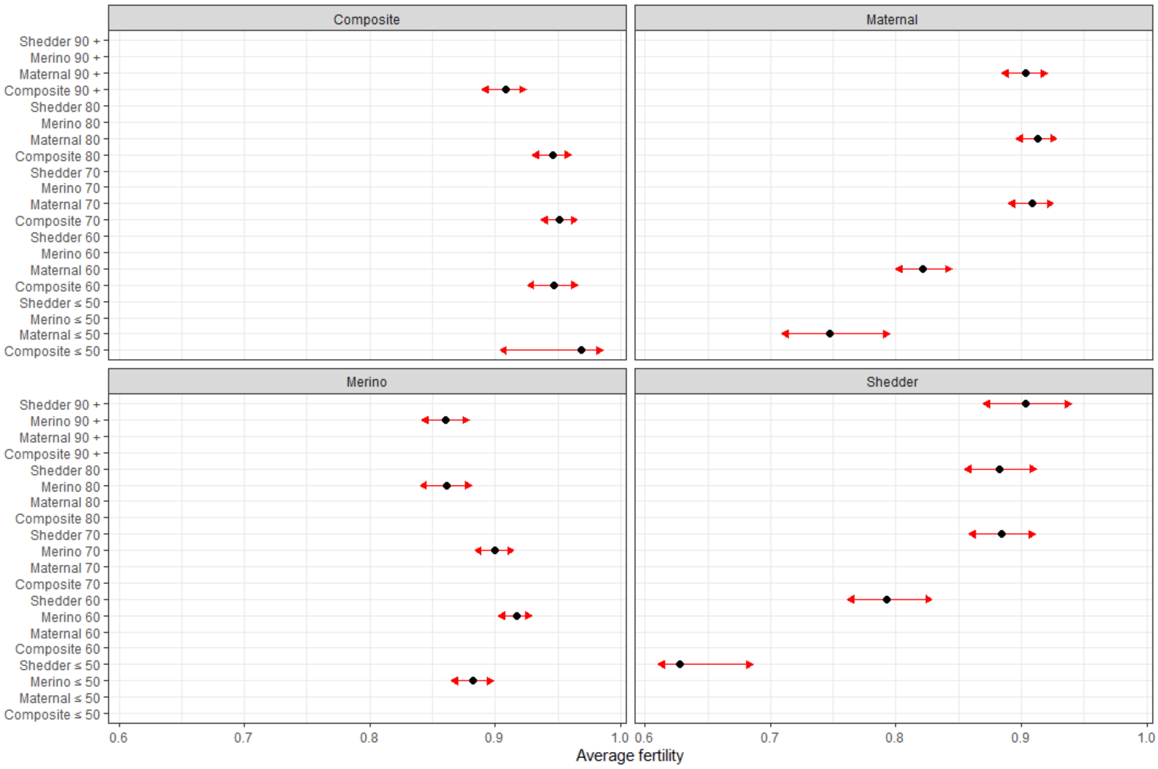

Figure 11. Pairwise comparisons for breed and liveweight class, reported for the least square mean (solid diamond) for ewe fertility. Arrows indicate standard errors and are not different when overlapped.

3.2.3.4 Breed x BCS

There was no difference in fertility in Composite ewes across the full BCS range (Fig. 12). In contrast to that, Maternal ewes have a limiting return in ewes heavier than BCS 3.75, while there was no statistical difference between all classes 3.0 to 3.25 and greater. The fertility of Merino ewes was not different between BCS classes 2.25 to 2.75 and up to 4.0 to 4.25, however, ewes in BCS 4.5+ had a lower fertility and the mean fertility was declining after BCS 3.75. In Shedder ewes there appear to be clusters with no difference in fertility between BCS classes 2.5 to 2.75 through to BCS 3.5 to 3.75, however, the highest fertility was found in ewes 4.0 to 4.25.

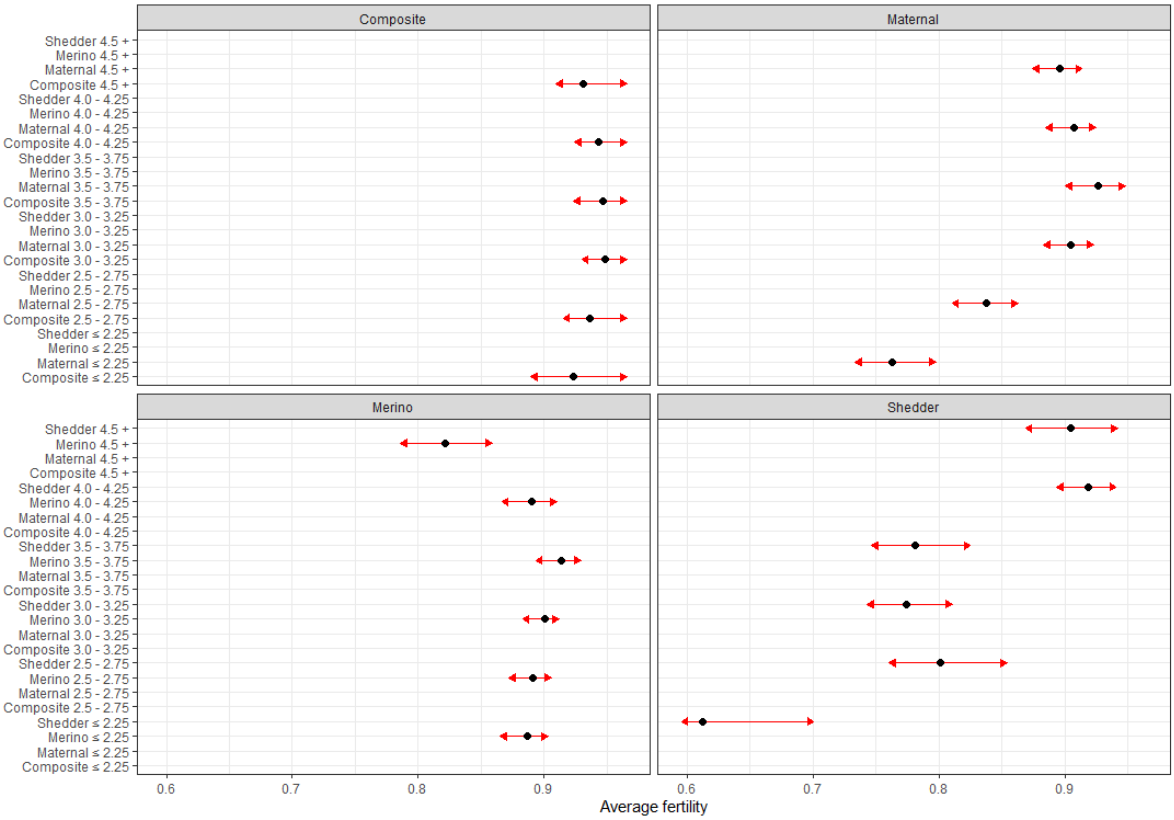

Figure 12. Pairwise comparisons for breed and body condition score class, reported for the least square mean (solid diamond) for ewe fertility. Arrows indicate standard errors and are not different when overlapped.

3.2.3.5 Season x Liveweight

The fertility of autumn- and spring-mated ewes was at its highest in the 70 kg class and there was no statistical difference in fertility in heavier classes, although the mean fertility did decline (Fig. 13). The fertility of summer-mated ewes did not differ in the liveweight classes 60, 70, 80 and 90+ kg, although the highest level of fertility was found in the 80 kg class.

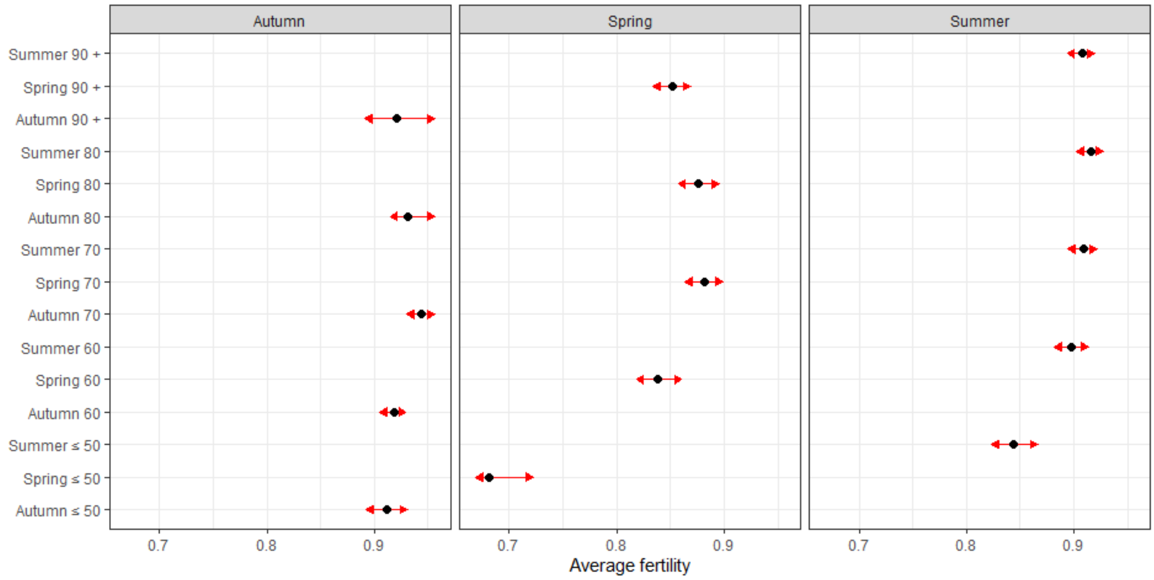

Figure 13. Pairwise comparisons for season and liveweight class, reported for the least square mean (solid diamond) for ewe fertility. Arrows indicate standard errors and are not different when overlapped.

3.2.3.6 Season x BCS

The fertility of ewe mated in autumn and spring did not differ between BCS classes 3.0 to 3.25 and heavier, but fertility was lower in leaner ewes. In summer mated ewes, there was no difference in fertility in ewes 2.5 to 2.75 and heavier (Fig. 14).

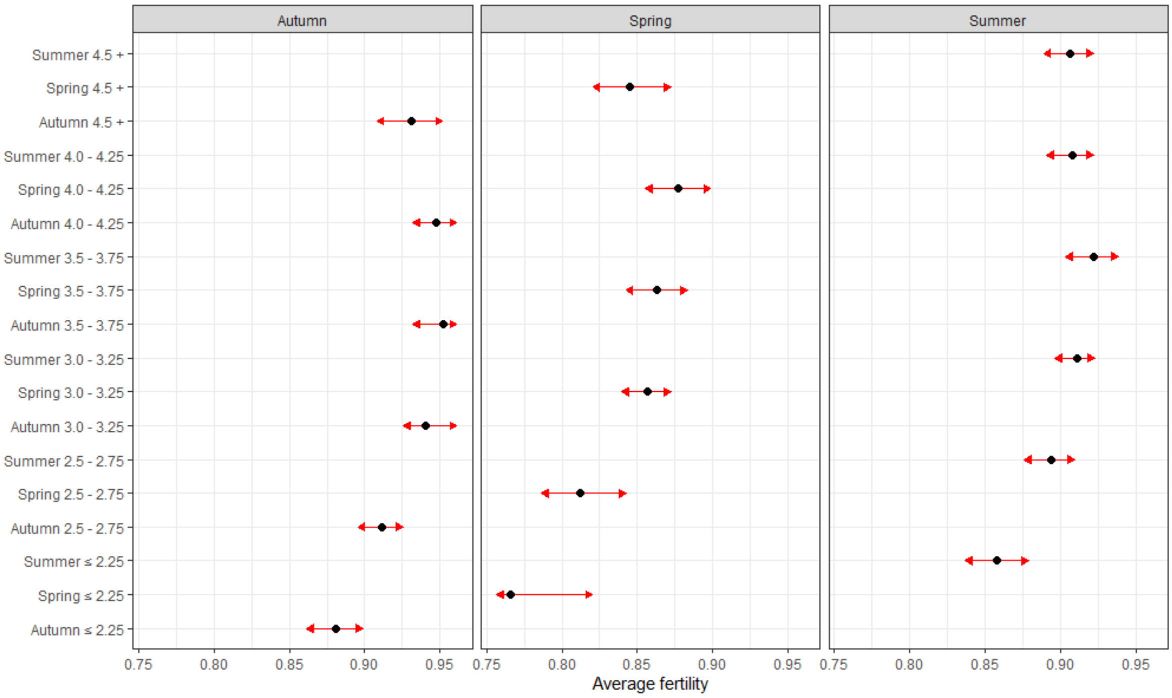

Figure 14. Pairwise comparisons for season and body condition score class, reported for the least square mean (solid diamond) for ewe fertility. Arrows indicate standard errors and are not different when overlapped.

3.2.4 Pairwise comparisons – Litter size

3.2.4.1 Breed x Liveweight

As Composite ewes increased in liveweight, their average litter size significantly decreased (Fig. 15). In contrast, litter size continued to increase in heavier Maternal ewes, but there was no difference in litter size between Maternal ewes that were in the 70, 80 and 90+ kg liveweight classes. Litter size increased in Merinos and Shedder breeds as liveweight increased from ≤50 kg to 70 kg but did not increase thereafter and in fact declined numerically in the Merino.

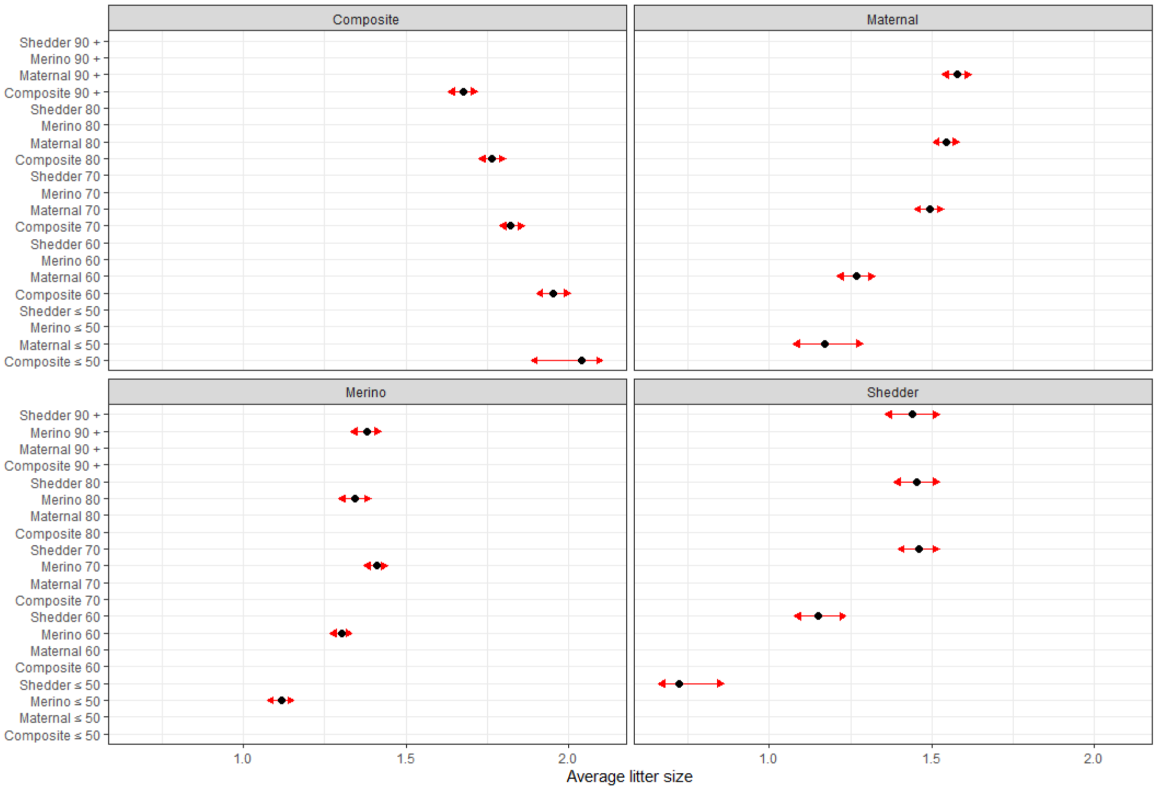

Figure 15. Pairwise comparisons for breed and liveweight class (kg), reported for the least square mean (solid diamond) for litter size (lambs scanned per ewe scanned). Arrows indicate standard errors and are not different when overlapped.

3.2.4.2 Breed x BCS

The average litter size was highest in the Composite with BCS 3.0 to 3.25, but there was no difference between BCS 2.5 to 2.75 and condition scores heavier than 3.5 (Fig. 16). In Maternal ewes, litter size did not significantly differ in ewes BCS 3.0 to 3.25 and heavier, while ewes 2.5 to 2.75 and leaner had a significantly lower litter size. Among the Merino ewes, litter size was highest in the ewes with BCS 3.5 to 3.75 and 4.0 to 4.25, while ewes BCS 4.5 and heavier had a mean litter size that did not differ from ewes 3.0 to 3.25 and leaner. Shedder flocks had their highest litter size when BCS was 4.0 to 4.25 and heavier than BCS 4.5.

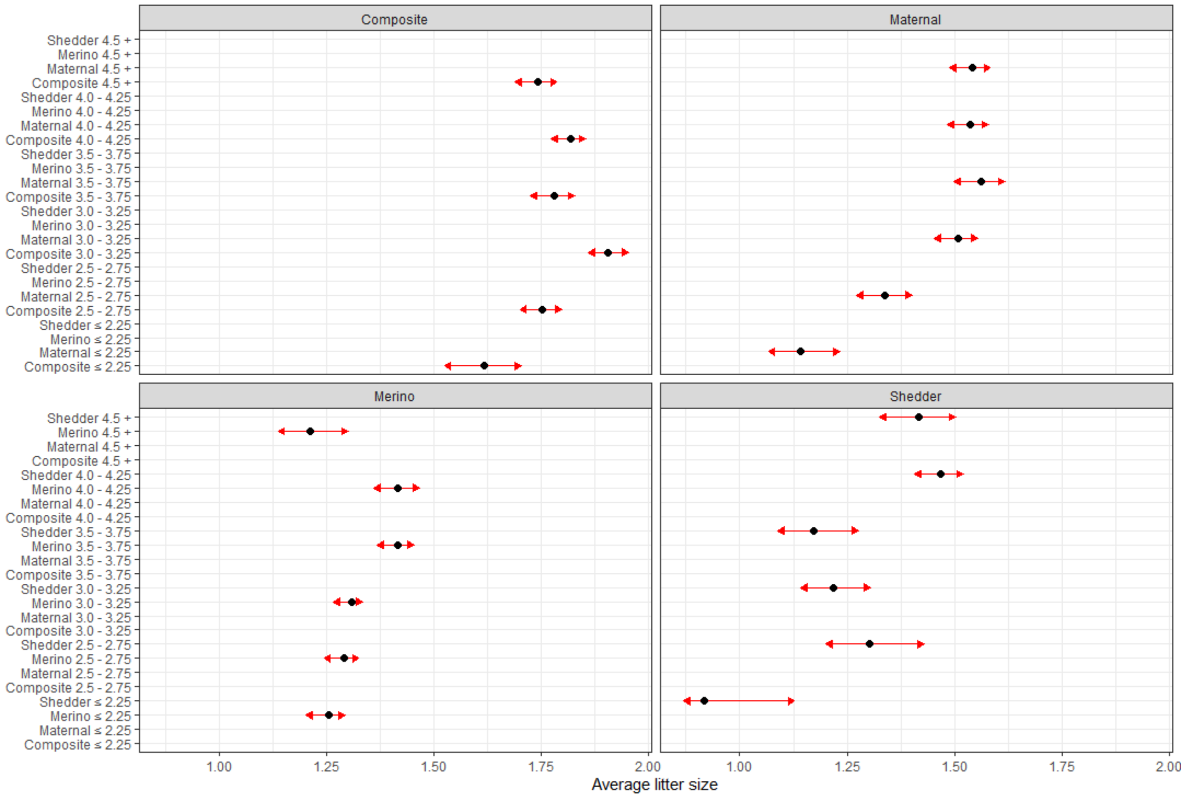

Figure 16. Pairwise comparisons for breed and body condition score class, reported for the least square mean (solid diamond) for litter size (lambs scanned per ewe scanned). Arrows indicate standard errors and are not different when overlapped.

3.2.4.3 Season x Liveweight

Litter size increased with liveweight in autumn- and spring-mated flocks and was maximal in 70 kg ewes, but no statistical differences were observed in heavier weight ewes. Summer-mated ewes had the highest litter size when 80 kg (Fig. 17).

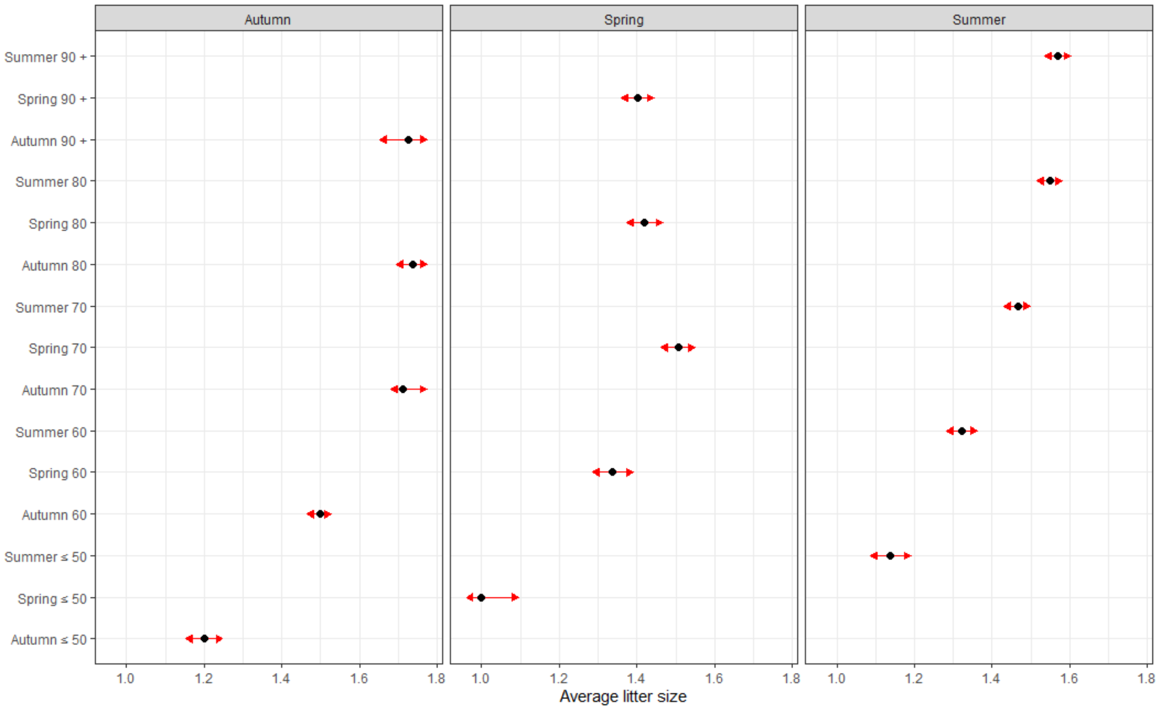

Figure 17. Pairwise comparisons for season and liveweight class (kg), reported for the least square mean (solid diamond) for litter size (lambs scanned per ewe scanned). Arrows indicate standard errors and are not different when overlapped.

3.2.4.4 Season x BCS

When mated in autumn, ewes with the highest litter size were BCS 4.0 to 4.25, but if mated in spring the highest litter size was found to be ewes in BCS 3.0 to 3.25, while in between these targets is the summer mated flock, with an optimal BCS of 3.5 to 3.75 (Fig. 18). Once meeting those optimal condition score, there were no statistically significant increases in litter size as the ewes were fatter. There are clear penalties for litter size as BCS decreased from the optimal for each season.

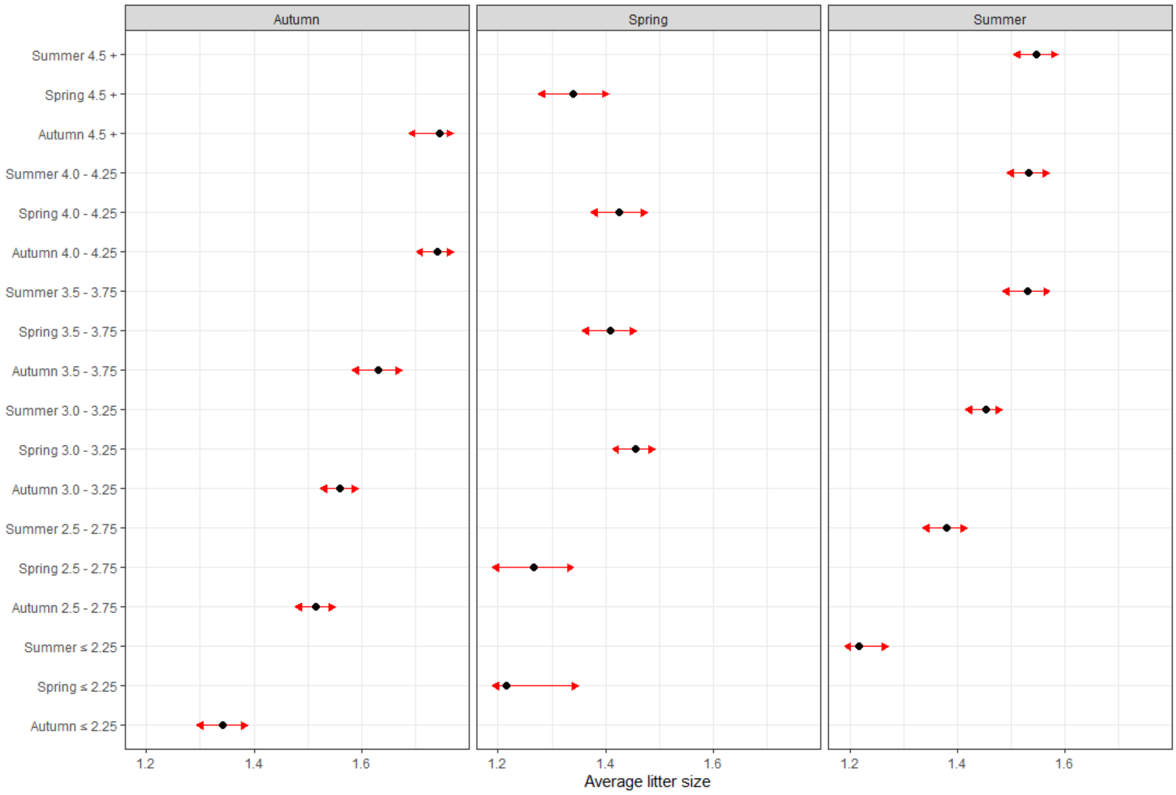

Figure 18. Pairwise comparisons for season and body condition score class, reported for the least square mean (solid diamond) for litter size (lambs scanned per ewe scanned). Arrows indicate standard errors and are not different when overlapped.

3.2.5 Trivariate analysis

3.2.5.1 Trivariate analysis results - Fertility

Composite flocks

Only one spring-mated Composite flock was recorded in the field study, limiting the power of analysis and interpretation of the results. Neither liveweight (P = 0.83), BCS (P = 0.5) or their interaction were significant (P = 0.18).

Fertility in summer-mated Composites did vary with liveweight (P < 0.05) and tended to vary with BCS (P < 0.1) and the interaction was not significant.

In all summer-mated Composite flocks, fertility decreased as liveweight increased (Fig. 19). At the same liveweight, small increases in fertility are observed as BCS increases. In autumn-mated Composite flocks, neither BCS (P = 0.11), liveweight (P = 0.69) or their interaction (P = 0.59) had significant effects on fertility. Examining Figure 19 suggests three flocks are low in their response to changes in liveweight (Sim_CW, CSU_RI, And_WV), while two flocks are moderate in that response (All_CW, Chr_CW) and the rest are highly responsive.

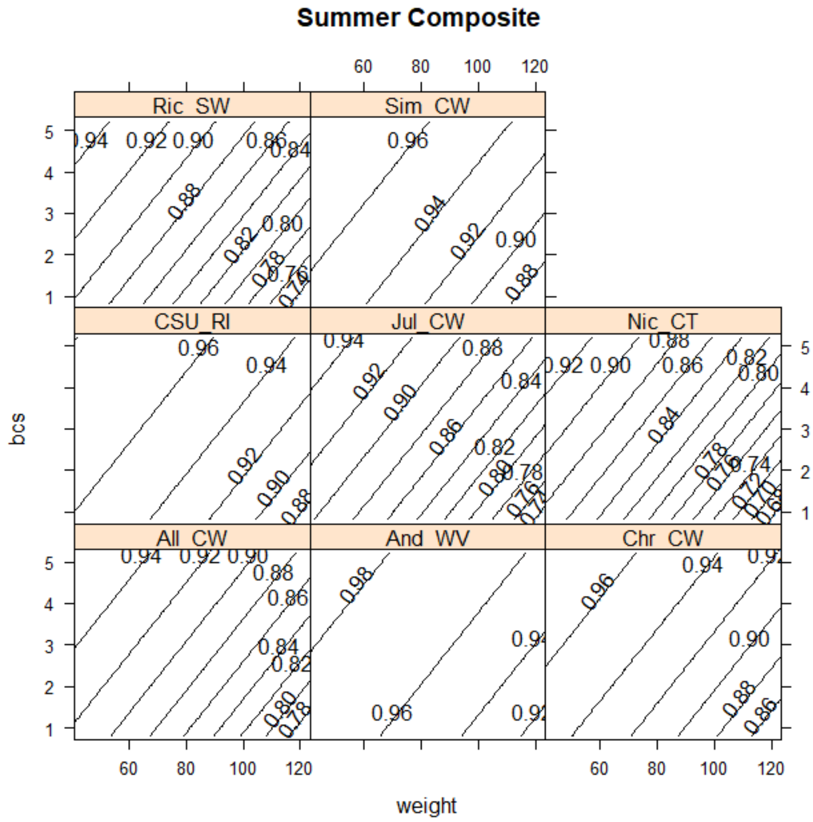

Figure 19. Contour plot displaying the probability for fertility in summer-mated Composite flocks across the range of liveweight (kg) and body condition scores (BCS).

Maternal flocks

In spring-mated Maternal flocks, liveweight (P = 0.37) and BCS (P = 0.28) and their interaction (P = 0.12) had no significant effects on fertility.

In summer-mated flocks, the interaction of liveweight and BCS was significant (P = 0.002) and is presented in Figure 20. There were eight summer-mated Maternal flocks assessed and of these two could be considered moderate fertility (Ric_WS and Mic_CW) and six are high fertility. One flock appears to be highly responsive to changes in BCS or liveweight (Mic_CW), while one flock may be lowly responsive (Jon_LM) and the rest being moderate in their response.

In autumn-mated Maternal flocks the interaction between liveweight and BCS was significant (P < 0.001) and is presented in Figure 21. The four flocks assessed in autumn include one low fertility flock (Ham_MO) and three are high fertility. Two flocks are lowly responsive to the variates (And_CT, Guy_CW), one flock is moderately responsive (Jon_WV) and one flock is highly responsive (Ham_MO).

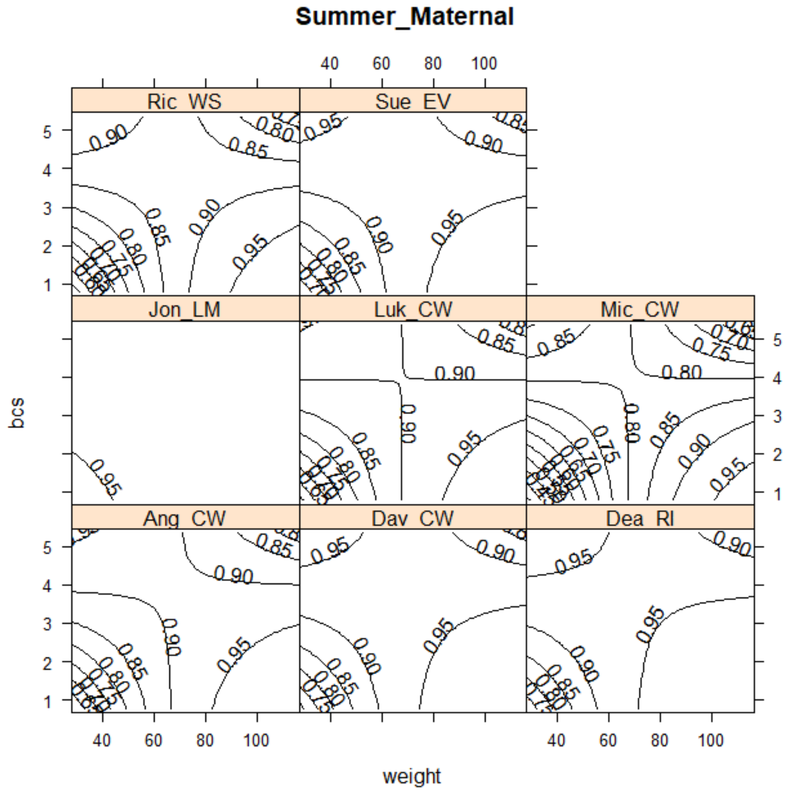

Figure 20. Contour plot displaying the probability for fertility in summer-mated Maternal flocks across the range of liveweight (kg) and body condition scores (BCS).

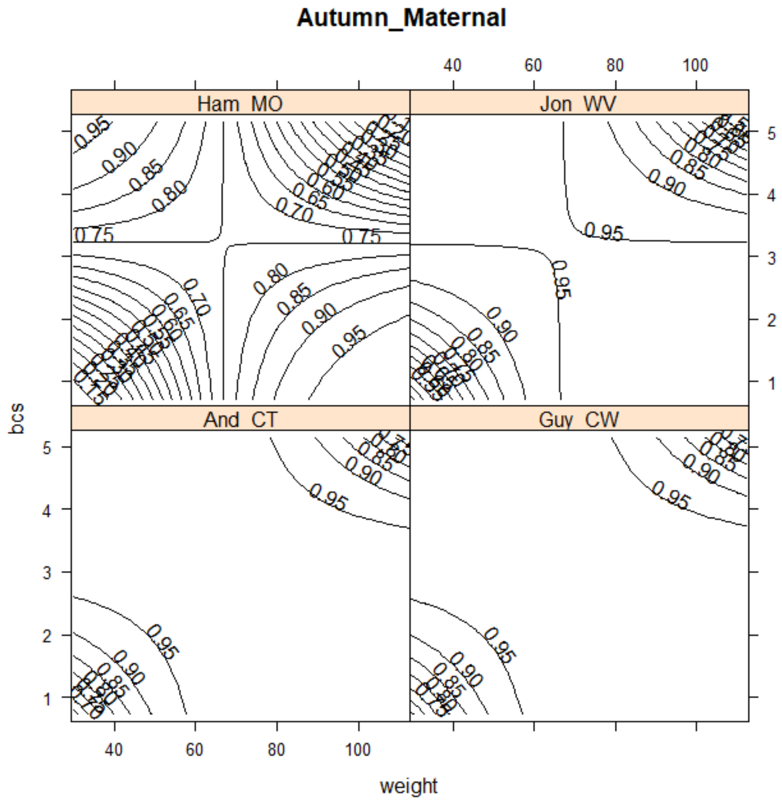

Figure 21. Contour plot displaying the probability for fertility in autumn-mated Maternal flocks across the range of liveweight (kg) and body condition scores (BCS).

Merino flocks

In the spring-mated Merino flocks, the interaction between liveweight and BCS was trending towards significance (P = 0.067) and the relationships are visualised in Figure 22. Interpretation of the relationships in Figure 22 should be made with some caution. There were three low fertility flocks (JamB_CW, JamK_RI, Ang_WE), three flocks are moderate fertility (Rob_SI, JamS_SA, Dre_MO) and one flock is high fertility (And_CW). One flock might be considered low response (And_CW), two flocks appear to be moderately responsive (Rob_SI, and JamS_SA) and the remaining flocks appear highly responsive to changes in BCS or liveweight.

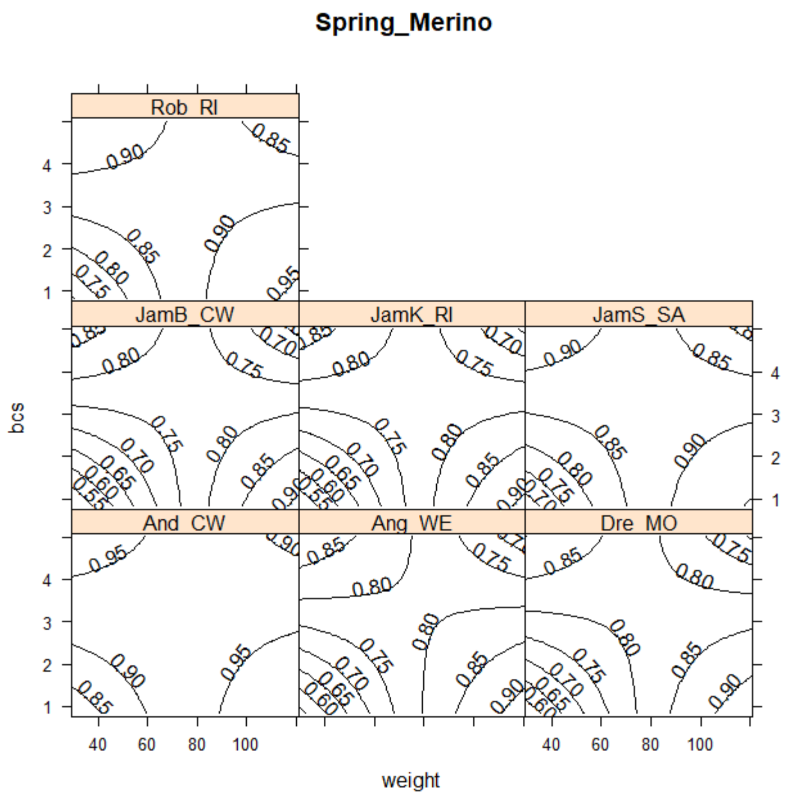

Figure 22. Contour plot displaying the probability for fertility in spring-mated Merino flocks across the range of liveweight (kg) and body condition scores (BCS).

For the flocks mated in summer, the interaction between liveweight and BCS was significant (P = 0.038) and the relationships are presented in Figure 23. There were eight Merino flocks assessed and of these, four had moderate fertility (Pet_RI, Jam_SA, Pet_NW, Ian_WV) and the rest were high fertility (Rod_EM, Pau_CW, Ala_YV, Ann_WE). There was one flock with low responsiveness in fertility with changes to liveweight and BCS (Ala_YV), three flocks were moderate in their response (Rod_EM, Pau_CW, Ann_WE) and the remaining four flocks were highly responsive.

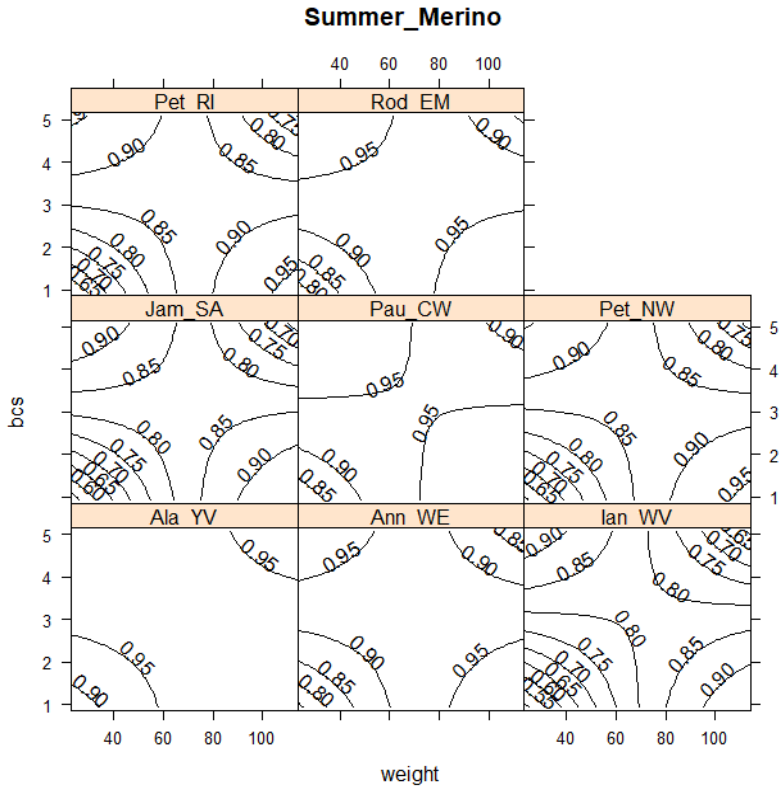

Figure 23. Contour plot displaying the probability for fertility in summer-mated Merino flocks across the range of liveweight (kg) and body condition scores (BCS).

In Autumn-mated Merino flocks, fertility varied significantly with BCS (P = 0.029) and the interaction of liveweight and BCS was also significant (P < 0.001). Figure 24 represents the interaction and shows all autumn-mated Merino flocks display uniformity in their trivariate responsive for fertility. All flocks had high fertility and were moderately responsive the changes in liveweight and BCS. Fertility was sensitive in light weight ewes that were lean, where small improvements in BCS or liveweight lead to large (~10%) improvements in fertility. Concurrently, there was limited variation in the fertility of ewes that were forward in condition BCS >3, or heavier than 60 kg.

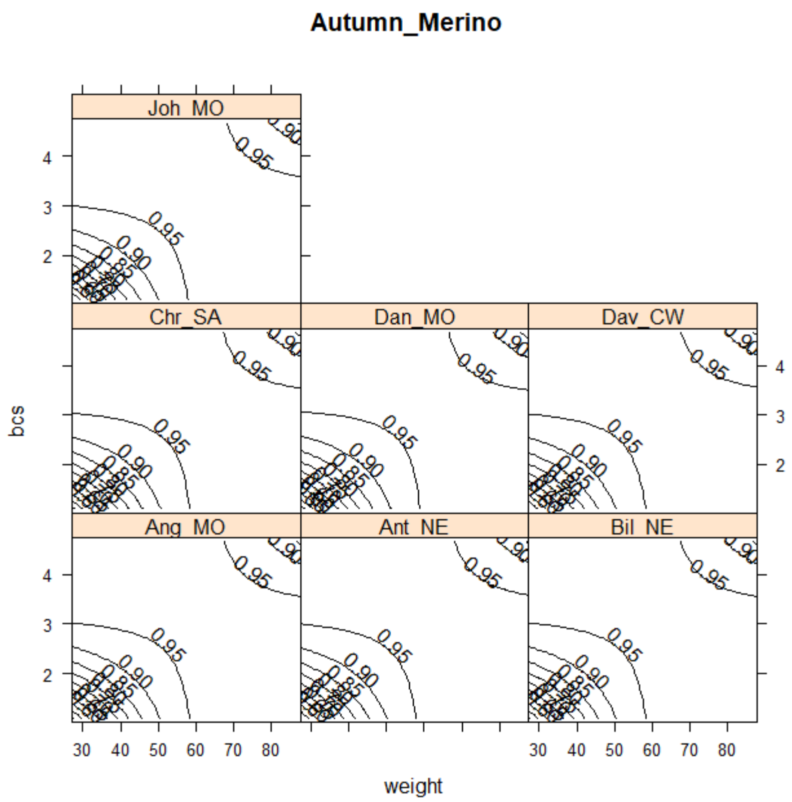

Figure 24. Contour plot displaying the probability for fertility in autumn-mated Merino flocks across the range of liveweight (kg) and body condition scores (BCS).

Shedder flocks

There were two spring-mated flocks, where liveweight was the only significant term (P < 0.001) and there was no significant interaction. No plots were created to describe the relationship.

No summer-mated shedder flocks engaged in the field study.

Three shedder flocks were assessed for autumn-mating where BCS (P = 0.0013) and the interaction between liveweight and BCS (P = 0.002) were significant. Figure 25 presents the relationships and shows that there was one high fertility flock (Cha_MO), one moderate fertility flock (Phi_WE) and one low fertility flock (Joh_WV). One flock was low in their fertility response to the variates (Cha_MO), while the other two flocks were highly responsive. In the highly responsive flocks, fertility increased in light liveweight ewes as BCS increased from 2 to 3 score by 20-25%, and was highest in light ewes when they were more forward in BCS, whereas very high liveweight ewes had higher fertility as BCS decreased.

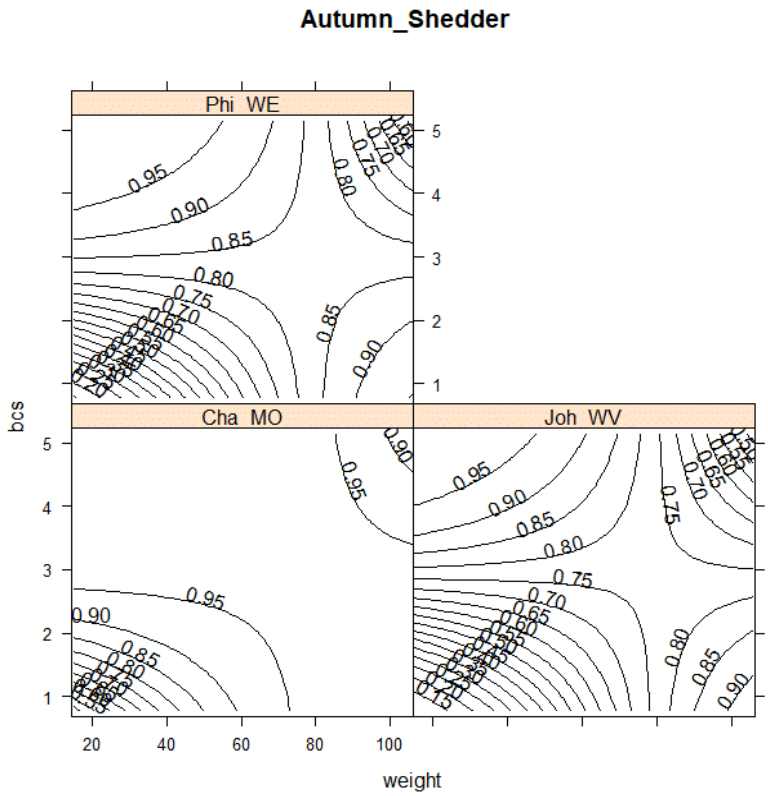

Figure 25. Contour plot displaying the probability for fertility in autumn-mated Maternal flocks across the range of liveweight (kg) and body condition scores (BCS).

3.2.5.2 Trivariate analysis results – Litter size

Logistic regression was used to analyse the probability of having multiple fetuses. Analyses were performed within season and included all breeds. The trivariate analysis for litter size shows the interactions between weight and BCS at mating for each breed and season and Figure 26 shows the probability of having multiple fetuses in deciles. The figure visually shows that each season has a particular pattern for the relationship between weight and BCS. From Figure 26, there appears to be 5 response patterns. Notable patterns include autumn Merino; spring Maternal, Merino and Shedder; and summer Composite, Maternal and Merino including autumn Maternal.

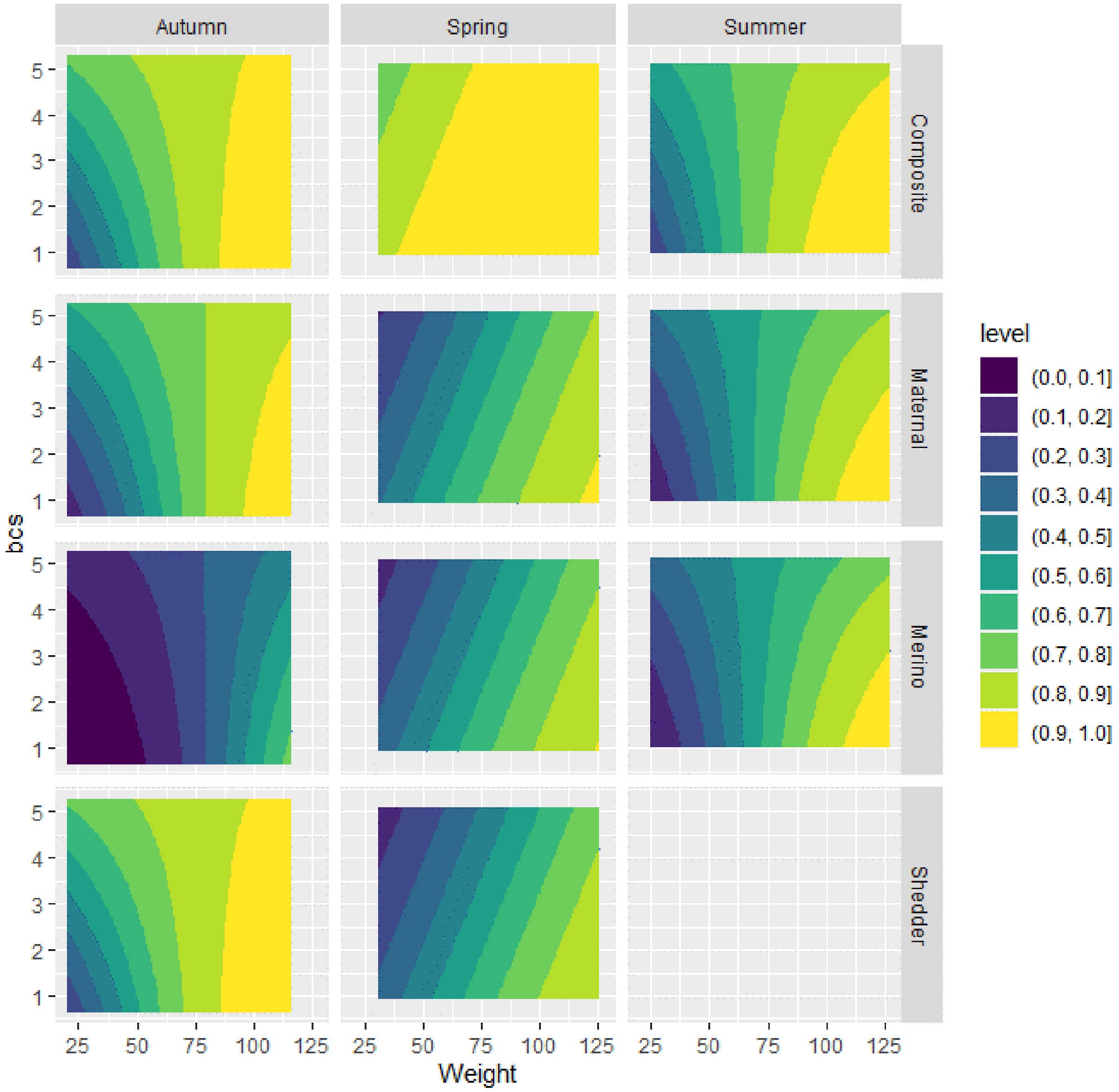

Figure 26. The probability of having multiple (2 or more) fetuses within breeds and seasons of mating, across the range of liveweight (kg) and body condition scores (BCS). Colour ranges are reported in deciles. Darker colours indicate lower probabilities, lighter colours are higher probabilities.

Spring

In spring-mated flocks, liveweight ($P < 0.001$), breed ($P < 0.001$) and BCS ($P < 0.001$) significantly affected the probability of having multiple fetuses. The interaction of liveweight and BCS were not significant ($P = 0.23$). This can be explained in examination of Figure 26, which shows parallel changes in the probability of having multiple fetuses as both weight and BCS are increasing for Maternal, Merino and Shedder breeds.

When compared to Composite ewes, the probability of having two or more fetuses was 89% less likely in Maternal ewes, 92% less likely in Merino and 94% less likely in Shedders. Caution is required when interpreting this result because only one Composite flock was assessed in spring and that flock used Regulin™ and their ewes were highly fecund genotype bloodline (Multimeat).

The majority of spring mated flocks were of the Merino breed and there was significant variation between flocks. Figure 27 shows a distinct linear pattern to the response in the probability of multiple fetuses, suggesting decreasing probabilities as BCS increases, but increasing probabilities as liveweight increases.

Summer

The significant factors affecting litter size in summer-mated flocks included liveweight ($P < 0.001$) and breed ($P < 0.05$). BCS was not signficant but the interaction of liveweight x BCS was ($P < 0.001$, Fig. 28). Merino ewes tended to be more likely (46%) to have fewer multiple fetuses ($P = 0.052$), while there were no Shedder flocks to examine in the summer data. Figure 26 shows for Composites, Maternal and Merino breeds, there is a response in the probability of having multiple fetuses in light weight ewes, as BCS increases. In the Composites sheep, there is little further improvement in ewes heavier than 60 kg, whereas in Maternal and Merino ewes, the probability of having multiple fetuses continues to improve in heavier weight ewes but when BCS is also decreasing.

Autumn

The significant factors affecting litter size in autumn-mated flocks included liveweight ($P < 0.001$), breed ($P < 0.001$), BCS ($P < 0.01$) and the interaction of liveweight x BCS ($P < 0.05$). Maternal ewes did not differ from Composite ewes in the probability of having 2 or more fetuses, while Merino ewes was 69% less likely than Composites and Shedder ewes were 46% less likely as Composites. There were signficant differences between each flock within breed. Figure 29 reports the probabilities of having multiple fetuses for each breed and the interaction of liveweight and BCS. At lower liveweights, the probability of having multiple fetuses increased when BCS increased, while at heavier livweights, the probability of multiple fetuses decreased as BCS increased. The patterns suggest that at a liveweight around 60 - 70 kg there is little response as BCS changes. Furthermore, it is clear that some flocks have inherently low reproduction rates, while others were much higher. The Merino and Shedder flocks surveyed appear more variable than the Maternal and Composite flocks. One Merino flock appears to respond to liveweight and BCS similarly to Composite and Maternal flocks, as does one Shedder flock, while the two other Shedder flocks appear to respond similarly to Merinos.

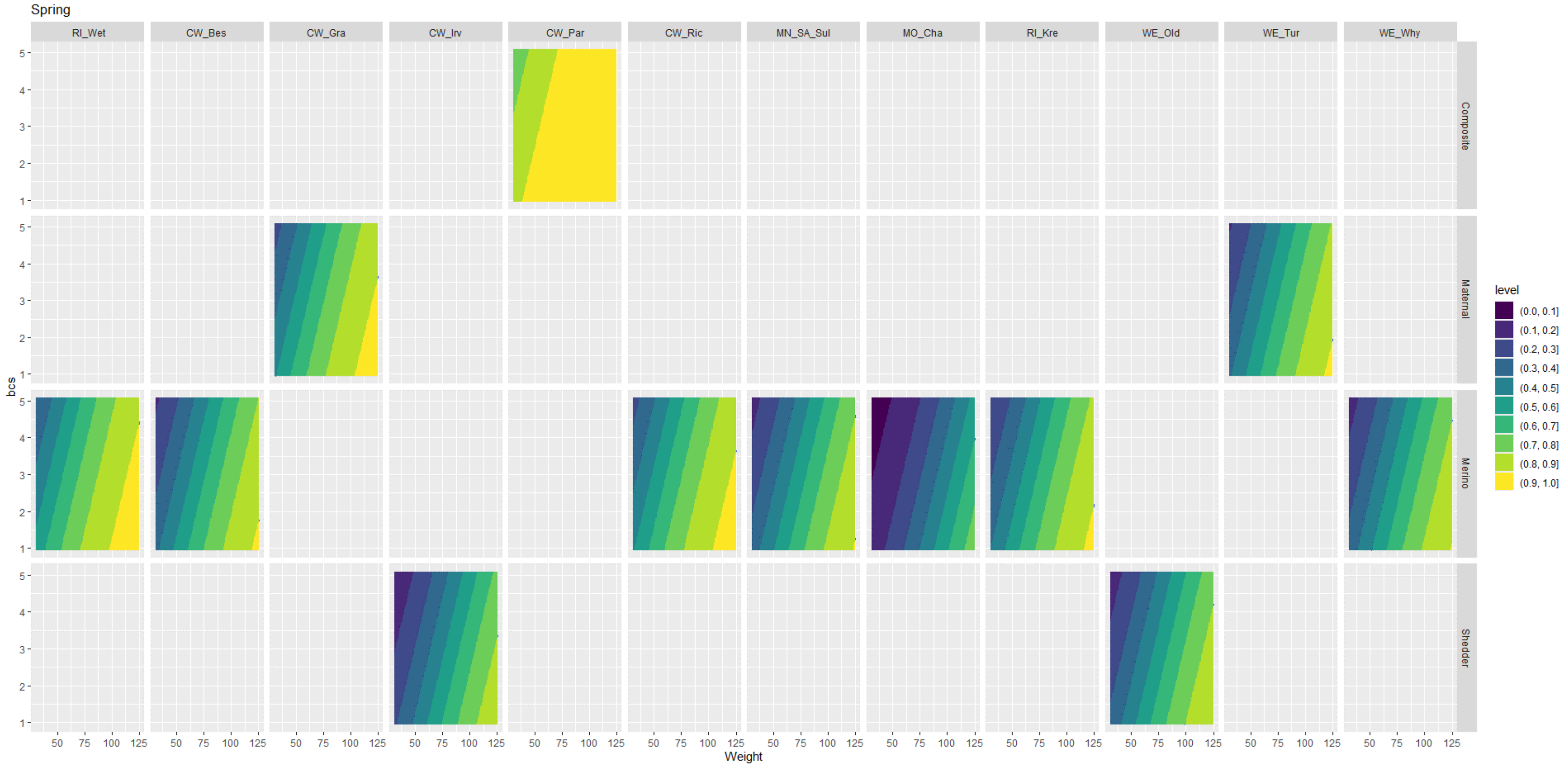

Figure 27. The probability of having multiple (2 or more) fetuses within breeds for spring-mated flocks, across the range of liveweight (kg) and body condition scores (BCS). Colour ranges are reported in deciles. Darker colours indicate lower probabilities, lighter colours are higher probabilities.

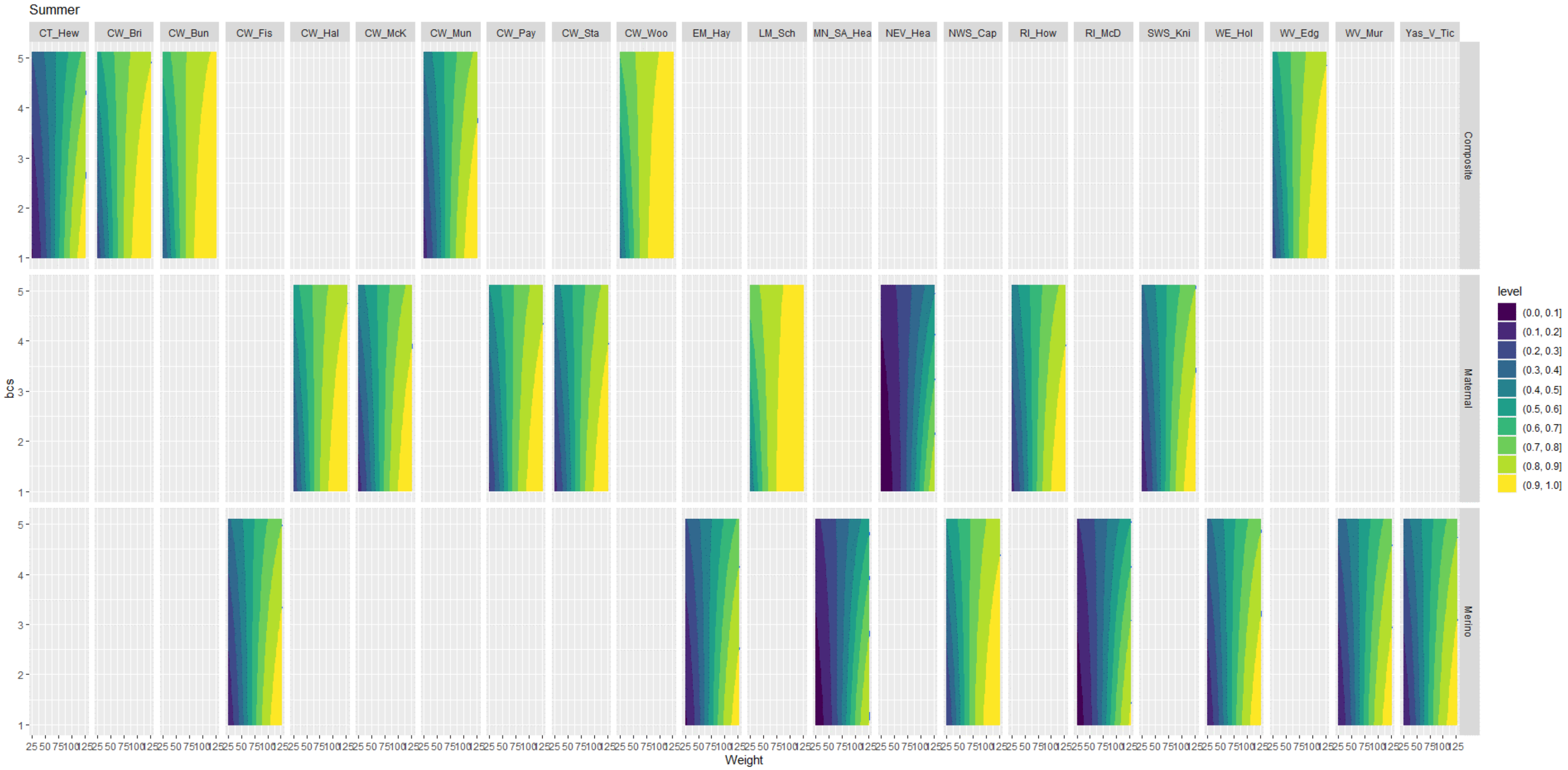

Figure 28. The probability of having multiple (2 or more) fetuses within breeds for summer-mated flocks, across the range of liveweight (kg) and body condition scores (BCS). Colour ranges are reported in deciles. Darker colours indicate lower probabilities, lighter colours are higher probabilities.

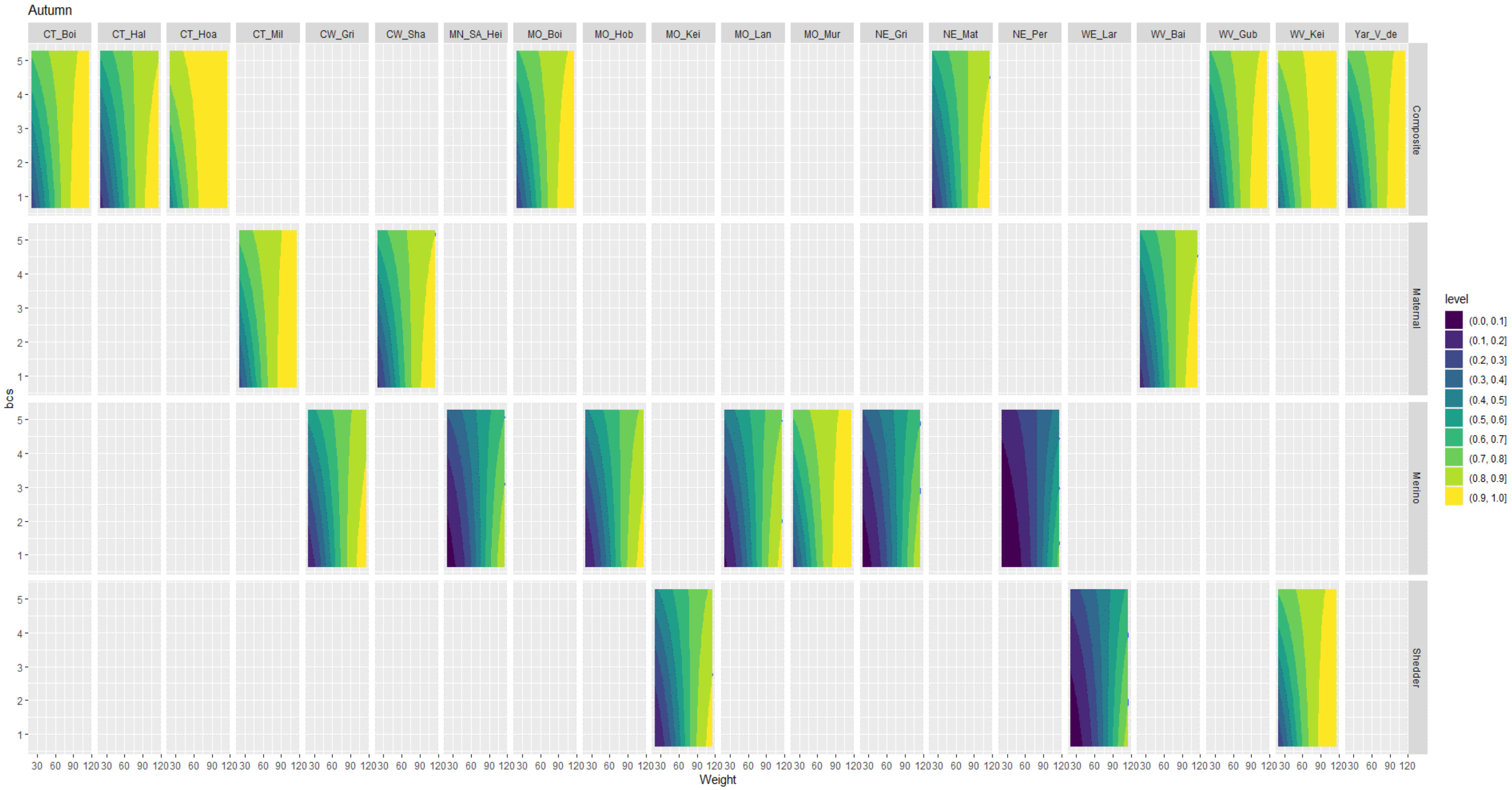

Figure 29. The probability of having multiple (2 or more) fetuses within breeds for autumn-mated flocks, across the range of liveweight (kg) and body condition scores (BCS). Colour ranges are reported in deciles. Darker colours indicate lower probabilities, lighter colours are higher probabilities.

3.2.6 Bayesian Network analysis

Bayesian Network (BN) analysis was used to explore the interrelationships of the variables using Netica software (Norsys Software Corp, 2021). A BN model is a graphical representation of a joint probability distribution of all the variables. The variables are represented by nodes which are linked based on probabilistic dependency between two associated variables (Kjærulff & Madsen, 2013). Since a BN model represents a joint probability of the variables, inferential analysis may be performed by fixing the values of a set of selected variables (similar to fixing the values of those predictor/independent variables in a regression model), then the values of remaining variables (equivalent to the response/dependant variable) in the BN model can be estimated.

The most influential factor in determining binary pregnancy outcomes (pregnant or non-pregnant) and binary litter size outcomes (single or multiple) can be investigated using a BN model with respect to the potential factors that may affect the outcome, such as breed, mating BCS, mating liveweight (weight), mating season (season), region, seasonal conditions during mating (during) and ram percentage (ram) (Fig 30). Mating liveweight, BCS and ram percentage were factored as categorical data. The BN software enables scenario testing to quantify the most important factors affecting that outcome. Sensitivity to findings enables ranking of impacts of other variables on a selected target variable. The sensitivity analysis outcomes are presented in Table 13 with a list of percentages values (ranked from highest to lowest) representing the strength of association between those evidence variables and the target variable. The sensitivity analysis reports values (%), which are similar to a goodness of fit, and represents the proportion of variation in the response variable being explained by those predictor variables.

A sensitivity analysis was performed for pregnancy outcome and litter size (of positive (‘1’) pregnancy outcomes), respectively, to quantify the strength of the association between the interrelated factors breed, mating BCS, mating liveweight, mating season, region, seasonal conditions during mating and ram percentage.

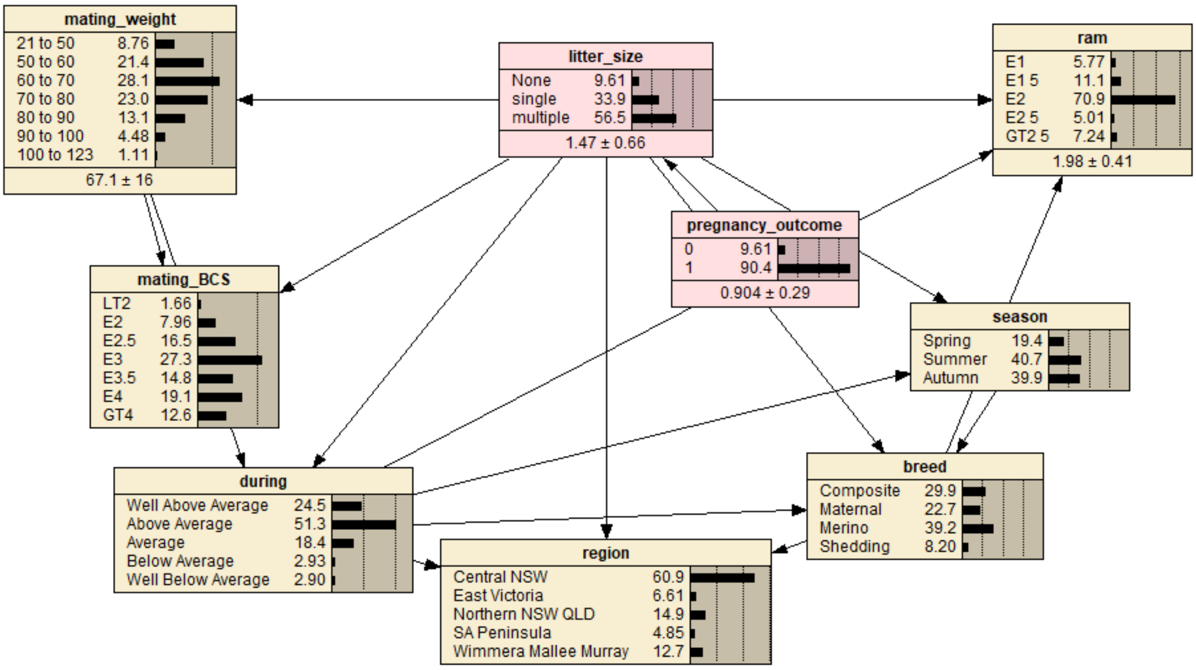

Figure 30. A predictive Bayesian Network model for the full ewe dataset representing interrelationships between ewe pregnancy outcome and litter size calculated for four breeds, seven mating BCS and mating weight levels, three mating seasons, five broad regions, five

subjective producer described seasonal conditions during mating and ram percentage utilised at mating. Letter prefixes of levels within nodes are defined as: LT = less than, E = a range of values around the displayed value and GT = greater than, further description of levels are displayed in Tables 15-18.

Based on the sample data, by first excluding the pregnancy outcome variable and designating the litter size as the target variable, the Netica inbuild TAN (Tree Augmented Naïve Bayes Net) algorithm was employed to specify a BN model structure; the fertility then was manually added into the model as the parent node of the litter size node; finally the BN model was completed by employing the inbuilt EM (Expectation-Maximization) algorithm to do the model parameter estimation. Thus, the resultant BN model should have the best prediction performance given the sample data. Further, the BN model was refined based on *a priori* knowledge of the data by manually adding three links between associated variables: (1) link between 'season' and 'breed'; (2) link between 'breed' and 'region'; and (3) link between 'breed' and 'ram'. The resultant BN model is presented in Fig 30.

The sensitivity analyses for pregnancy outcome and litter size of pregnant ewes (pregnancy outcome '1' selected) allowed a quantitative comparison of the factors breed, mating BCS, mating weight, mating season, region, seasonal conditions and ram percentage to determine the most influential factor (Table 13). Overall, the Netica sensitivity to findings function found that the factors explored explained little of the predicted pregnancy outcome and litter size. Pregnancy outcome and litter size of pregnant ewes were each most influenced by ewe breed given the absolute influence level being very low. A series of subsequent sensitivity analyses were performed for pregnancy and litter size outcome of pregnant ewes of each breed to determine which factor was most influential (Table 14). Seasonal conditions during mating were most influential on pregnancy outcome for Composite and Shedder ewes, while region was most influential for Maternal ewes and mating season for Merino ewes. Mating liveweight was most influential on litter size of pregnant Composite, Maternal and Merino ewes while seasonal conditions during mating were most influential on Shedder ewe breeds.

Table 13. Bayesian network Sensitivity analysis to determine how much the Pregnancy outcome and Litter size nodes were influenced by each of the observed variables for Pregnancy outcome and Litter size. Mutual information (MI) is and percentage (P).

	Pregnancy outcome		Litter size	
Node	**MI**	**P (%)**	**MI**[A]	**P (%)**[B]
Breed	0.00616	1.35	0.0581	6.09
During	0.00225	0.493	0.0255	2.67
Mating BCS	0.00217	0.475	0.0111	1.16
Season	0.00611	1.34	0.00312	0.327
Mating weight	0.00302	0.662	0.0402	4.21
Ram	0.00425	0.931	0.00738	0.773
Region	0.00196	0.430	0.0323	3.38

[A] Mutual information is a measure of information shared between two random variables that quantifies the change in uncertainty on one provided the uncertainty of the other variable is known.

[B] The percentage values from the sensitivity analyses for a selected variable are broadly analogous to an adjusted R^2 from a regression analysis.

Table 14. Bayesian network Sensitivity analysis to determine how much the Pregnancy outcome and Litter size nodes were influenced by each of the observed variables for Pregnancy outcome and Litter size within each breed, Composite, Maternal, Merino, Shedding. Shaded numbers indicate the node which most influences Pregnancy outcome and Litter size for each breed, a dash (-) indicates no data for comparison.

	Composite				Maternal				Merino				Shedding			
	Pregnancy outcome		Litter size		Pregnancy outcome		Litter size		Pregnancy outcome		Litter size		Pregnancy outcome		Litter size	
Node	**MI**	**P (%)**	**MI**	**P (%)**	**MI**	**P (%)**	**MI**	**P (%)**	**MI**	**P (%)**	**MI**	**P (%)**	**MI**	**P (%)**	**MI**	**P (%)**
During	0.00804	2.48	0.00346	0.467	0.0100	1.98	0.00962	1.06	0.0126	2.60	0.0178	1.79	0.0186	3.06	0.0531	5.36
Mating BCS	0.00107	0.331	0.00486	0.656	0.00335	0.668	0.00683	0.76	0.00184	0.381	0.0126	1.26	0.00473	0.778	0.0115	1.15
Season	0.00278	0.858	0.0109	1.47	0.00142	0.284	0.0108	1.20	0.0182	3.75	0.00403	0.404	0.0000600	0.00965	0.0174	1.75
Mating weight	0.00268	0.826	0.0230	3.10	0.00394	0.785	0.0256	2.83	0.00372	0.769	0.0398	3.98	0.00383	0.629	0.0427	4.30
Ram	0.00339	1.04	0.00919	1.24	0.0191	3.81	0.0180	1.99	0.00613	1.27	0.0106	1.06	-	-	-	-
Region	0.00765	2.36	0.00148	0.199	0.0215	4.29	0.00886	0.980	0.000690	0.143	0.0226	2.26	0.0159	2.62	0.0734	7.40

[A] Mutual information is a measure of information shared between two random variables that quantifies the change in uncertainty on one provided the uncertainty of the other variable is known.

[B] The percentage values from the sensitivity analyses for a selected variable are broadly analogous to an adjusted R^2 from a regression analysis.

The model predicted relationship between Composite ewe litter size and each node is displayed in Table 15. As seasonal conditions improved above 'average' non-pregnant rate also increased, as identified by the sensitivity analysis (Table 14). 'Above average' seasonal conditions increased litter size, but 'well above average' conditions decreased litter size. A mating BCS 4, mating liveweight of 60-70 kg and ram percentage of 1.5% resulted in the lowest non-pregnant rates and highest multiple fetus rates. Mating in spring resulted in superior reproductive potential compared to autumn and then summer. Multiple rate did not appear to be regionally dependant. Optimum reproductive potential of Composite ewes across region and seasonal conditions was predicted to occur with a summer mating, 1.5% ram percentage, mating BCS 4 and mating liveweight of 60-70 kg.

Table 15. The estimated probabilities for Composite litter size (displayed as percentages) for each node when the different levels within each node are assumed in the Bayesian Network model. A dash (-) indicates data were not applicable for the respective level. The row total percentage value may be slightly different from 100% due to rounding errors.

Node	Level	Level description	Litter size		
			Non-pregnant	Single	Multiple
During	Well above average	Seasonal conditions described by producers during mating	10.4	23.3	66.2
	Above average		4.94	18.1	76.9
	Average		2.48	21.8	75.7
	Below average		-	-	-
	Well below average		-	-	-
Mating BCS	LT2	BCS <2	11.2	29.7	59.1
	E2	BCS 2-2.25	7.67	25.6	66.8
	E2.5	BCS 2.5-2.75	6.36	21.3	72.4
	E3	BCS 3-3.25	5.65	21.4	73.0
	E3.5	BCS 3.5-3.75	5.22	19.3	75.5
	E4	BCS 4-4.25	5.08	16.0	78.9
	GT4	BCS ≥4.5	6.55	16.5	76.9
Mating season	Spring	Season of mating	3.82	8.08	88.1
	Summer		7.50	23.9	68.6
	Autumn		4.66	17.1	78.3
Mating weight	21 to 50	21 to 49.5 kg	9.05	43.2	47.8
	50 to 60	50 to 59.5 kg	6.10	25.4	68.5
	60 to 70	60 to 69.5 kg	4.53	15.8	79.7
	70 to 80	70 to 79.5 kg	5.46	15.9	78.6
	80 to 90	80 to 89.5 kg	7.02	17.9	75.1
	90 to 100	90 to 99.5 kg	7.96	17.0	75.1
	100 to 123	≥100 kg	14.1	17.2	68.7
Ram	E1	1.0 to 1.25%	4.24	13.2	82.6
	E1.5	1.3 to 1.75%	2.37	22.4	75.2
	E2	1.8 to 2.3%	5.89	18.9	75.2
	E2.5	2.5%	11.7	35.4	52.9
	GT2.5	2.8 to 4.0%	-	-	-
Region	Central NSW		7.17	19.9	72.9
	East Victoria		6.90	17.9	75.1
	Northern NSW/QLD		1.73	26.0	72.3
	SA Peninsula		-	-	-
	Wimmera Mallee Murray		2.08	18.1	79.8

The model predicted relationship between Maternal ewe litter size and each node is displayed in Table 16. A 'well above average' season predicted the least non-pregnant ewes with the most fetuses, however 'above average' produced more non-pregnant ewes and fewer multiple fetuses compared to an 'average' season. A mating BCS 4, summer mating, mating liveweight of 60-70 kg and ram percentage of 2% resulted in the lowest non-pregnant rates and highest multiple litter rates. Non-pregnant rates and litter size was regionally impacted, as identified by the sensitivity analysis (Table 14). Optimum reproductive potential of Maternal ewes across region and seasonal conditions was predicted to occur with a summer mating, 2% ram percentage, mating BCS 4 and mating liveweight of 60-70 kg.

Table 16. The estimated probabilities for Maternal litter size (displayed as percentages) for each node when the different levels within each node are assumed in the Bayesian Network model. Level descriptions detail the data and naming conventions within each level of the model. A dash (-) indicates data were not applicable for the respective level. The row total percentage value may be slightly different from 100% due to rounding errors.

Node	Level	Level description	Litter size		
			Non-pregnant	Single	Multiple
During	Well above average	Seasonal conditions described by producers during mating	7.87	25.3	66.9
	Above average		15.5	32.4	52.1
	Average		10.1	35.2	54.6
	Below average		-	-	-
	Well below average		-	-	-
Mating BCS	LT2	BCS <2	22.7	37.5	39.8
	E2	BCS 2-2.25	16.1	34.9	49.0
	E2.5	BCS 2.5-2.75	13.1	30.7	56.3
	E3	BCS 3-3.25	10.9	30.8	58.3
	E3.5	BCS 3.5-3.75	9.51	28.5	61.9
	E4	BCS 4-4.25	9.19	24.6	66.2
	GT4	BCS ≥4.5	10.4	24.1	65.4
Mating season	Spring	Season of mating	13.9	31.2	54.8
	Summer		9.98	31.7	58.3
	Autumn		11.80	20.2	68.0
Mating weight	21 to 50	21 to 49.5 kg	18.5	51.8	29.7
	50 to 60	50 to 59.5 kg	13.60	36.4	50.0
	60 to 70	60 to 69.5 kg	9.79	26.5	63.7
	70 to 80	70 to 79.5 kg	9.81	25.0	65.1
	80 to 90	80 to 89.5 kg	9.93	24.4	65.7
	90 to 100	90 to 99.5 kg	9.90	21.9	68.2
	100 to 123	≥100 kg	17.7	23.1	59.2
Ram	E1	1.0 to 1.25%	30.10	25.8	44.1
	E1.5	1.3 to 1.75%	10.4	22.7	66.9
	E2	1.8 to 2.3%	8.35	24.9	66.8
	E2.5	2.5%	14.3	38.8	46.9
	GT2.5	2.8 to 4.0%	10.5	38.7	50.8
Region	Central NSW		10.1	25.9	64.1
	East Victoria		4.49	38.9	56.6
	Northern NSW/QLD		12.9	36.5	50.6
	SA Peninsula		-	-	-
	Wimmera Mallee Murray		30.1	25.8	44.1

The model predicted relationship between Merino ewe litter size and each node is displayed in Table 17. Seasonal conditions during mating had a varied impact on non-pregnant rate as indicated by the sensitivity analysis (Table 14). However, as conditions improved so did fetal number. A mating BCS 4, autumn mating, mating liveweight of 60-70 kg and ram percentage of 2% resulted in the lowest non-pregnant rates and highest multiple litter rates. Litter size may be regionally impacted. Optimum reproductive potential of Merino ewes across region and seasonal conditions was predicted to occur with a summer mating, 1.5% ram percentage, mating BCS 4 and mating liveweight of 60-70 kg.

Table 17. The estimated probabilities for Merino litter size (displayed as percentages) for each node when the different levels within each node are assumed in the Bayesian Network model. Level descriptions detail the data and naming conventions within each level of the model. A dash (-) indicates data were not applicable for the respective level. The row total percentage value may be slightly different from 100% due to rounding errors.

Node	Level	Level description	Litter size		
			Non-pregnant	Single	Multiple
During	Well above average	Seasonal conditions described by producers during mating	13.1	35.4	51.5
	Above average		6.6	50.3	43.1
	Average		14.2	42.1	43.7
	Below average		7.24	60.9	31.9
	Well below average		20.3	62.8	16.9
Mating BCS	LT2	BCS <2	17.7	55.8	26.5
	E2	BCS 2-2.25	12.8	54.8	32.4
	E2.5	BCS 2.5-2.75	11.3	50.2	38.5
	E3	BCS 3-3.25	9.66	50.5	39.8
	E3.5	BCS 3.5-3.75	9.05	46.2	44.8
	E4	BCS 4-4.25	9.28	39.8	50.9
	GT4	BCS ≥4.5	11.6	38.3	50.0
Mating season	Spring	Season of mating	16.3	38.9	44.8
	Summer		11.60	49.0	39.4
	Autumn		4.71	51.8	43.5
Mating weight	21 to 50	21 to 49.5 kg	14.2	66	19.8
	50 to 60	50 to 59.5 kg	9.93	55.4	34.7
	60 to 70	60 to 69.5 kg	8.33	42.3	49.3
	70 to 80	70 to 79.5 kg	9.25	39.4	51.4
	80 to 90	80 to 89.5 kg	12.10	39.1	48.8
	90 to 100	90 to 99.5 kg	15.10	34.4	50.5
	100 to 123	≥100 kg	17.9	32.1	50.0
Ram	E1	1.0 to 1.25%	14.50	62.1	23.5
	E1.5	1.3 to 1.75%	11.4	42.7	46.0
	E2	1.8 to 2.3%	8.60	46.5	44.9
	E2.5	2.5%	18.9	50.8	30.2
	GT2.5	2.8 to 4.0%	16.3	51.3	32.4
Region	Central NSW		9.82	42.4	47.8
	East Victoria		-	-	-
	Northern NSW/QLD		10.4	60.6	29.0
	SA Peninsula		12.5	50..5	37.0
	Wimmera Mallee Murray		11.8	39.3	48.8

The model predicted relationship between shedding ewe litter size and each node is displayed in Table 18. Improving seasonal conditions appeared to increase number of multiple fetuses, but non-pregnant rate also increased, as indicated by the sensitivity analysis (Table 14). A mating BCS 4, autumn mating and mating liveweight of 90-100 kg resulted in the lowest non-pregnant rates and highest multiple litter rates. Litter size may be regionally impacted. Optimum reproductive potential of shedding ewes across region and seasonal conditions was predicted to occur with a summer mating, 2% ram percentage, mating BCS 4 and mating liveweight of 60-70 kg.

Table 18. The estimated probabilities for Shedding litter size (displayed as percentages) for each node when the different levels within each node are assumed in the Bayesian Network model. Level descriptions detail the data and naming conventions within each level of the model. A dash (-) indicates data were not applicable for the respective level. The row total percentage value may be slightly different from 100% due to rounding errors.

Node	Level	Level description	Litter size		
			Non-pregnant	Single	Multiple
During	Well above average	Seasonal conditions described by producers during mating	-	-	-
	Above average		18.0	28.6	53.5
	Average		4.80	50.8	44.4
	Below average		-	-	-
	Well below average		15.8	59.0	25.1
Mating BCS	LT2	BCS <2	26.9	44.4	28.6
	E2	BCS 2-2.25	19.9	43.8	36.3
	E2.5	BCS 2.5-2.75	17.2	39.8	42.9
	E3	BCS 3-3.25	14.6	40.7	44.7
	E3.5	BCS 3.5-3.75	13.0	37.5	49.5
	E4	BCS 4-4.25	12.1	31.7	56.2
	GT4	BCS ≥4.5	12.4	31.8	55.8
Mating season	Spring	Season of mating	15.3	45.8	38.9
	Summer		-	-	-
	Autumn		14.70	32.7	52.6
Mating weight	21 to 50	21 to 49.5 kg	21.3	57.5	21.1
	50 to 60	50 to 59.5 kg	16.4	45.3	38.3
	60 to 70	60 to 69.5 kg	13.4	33.1	53.5
	70 to 80	70 to 79.5 kg	14.3	28.5	57.2
	80 to 90	80 to 89.5 kg	12.2	34.0	53.8
	90 to 100	90 to 99.5 kg	9.80	35.0	55.2
	100 to 123	≥100 kg	10.4	30.5	59.1
Ram	E1	1.0 to 1.25%	-	-	-
	E1.5	1.3 to 1.75%	-	-	-
	E2	1.8 to 2.3%	14.90	38.0	47.0
	E2.5	2.5%	-	-	-
	GT2.5	2.8 to 4.0%	-	-	-
Region	Central NSW		14.4	37	48.5
	East Victoria		-	-	-
	Northern NSW/QLD		9.69	54.5	35.9
	SA Peninsula		-	-	-
	Wimmera Mallee Murray		24.0	14.1	61.9

Across breeds, predicted multiple rates decreased when ewe body condition at mating exceeded BCS 4 and the corresponding non-pregnant and single-bearing ewe proportions increased. Similar observations were made for liveweight and ram percentage for each breed (except shedders where there was no variation in ram percentage). Taken together, the data suggests curvilinear relationships between reproduction outcomes and ewe liveweight, ewe BCS and ram percentage.

4. Farm system modelling

4.1 Methodology

AusFarm models have been developed for eight sites. These sites are Bookham, Bungarby, Condobolin, Glen Innes, Trangie and Narrandera in NSW, Hamilton in Victoria and Keith in South Australia.

The eight models had been created by other researchers and were revised to allow simulation of the specifics for this project. Requests were made to the creators to share the key components, such as soil and pasture components as well as outputs such as published reports that provide information about pasture growth rate and animal genotype descriptions. If we didn't receive the component files, we used published literature to set assumptions.

Published reports were sourced for Bookham, Bungarby, Glen Innes, Narrandera and Hamilton, and component data was shared for Bookham, Keith, Condobolin, Trangie and Narrandera. Base models were ground-truthed against existing publications or with subject matter experts.

For each site, the soil descriptors were taken from the Australian soil database, APSOIL, or previous modellers have described the soil components and those descriptions have been adopted in our models. Similarly, pastures have been defined by previous modellers and adapted for our purposes. BoM -derived weather data was input into Ausfarm, enabling the models to be examined for a meteorological period (1986-2020), with the first three years removed to permit the model to initialise.

At sites where mixed farming is typical, a cropping rotation has been modelled, which enables the sheep component to utilise grazing stubbles. When minimum ground cover targets are not met, the sheep are moved off paddocks and into containment systems and grain fed.

Stocking rate is optimised for each genotype and the season of mating. The optimum stocking rate was defined as the stocking rate at which peak gross margins ($/Ha) was achieved and the grain feeding, and pasture thresholds were also met. The grain feeding threshold, based on the (NSW Department of Primary Industries 2021) allowed up to 35 kg per head to be fed to Merino ewes and 42 kg per head for Maternal ewes in four out of ten years, which was also employed for the Composite ewe simulations. The pasture threshold that was developed by (Warn *et al.* 2006) was employed, ensuring at least 800 kg DM/Ha between 1st January and 30th April in eight out of ten years.

Three breeds were chosen for modelling. These were Merino (high fleece value; two liveweights, according to the environment); Maternal breeds (woolled crossbreds and woolled non-Merino purebred, BLM); and Composite (sheep with multiple breeds in their pedigree). It was intended to include shedding hair sheep but that genotype is not available in the GrazPlan packages due to insufficient data. The decision was made to not make assumptions about the performance of this genotype so it could not be modelled. The lack of parameters for this breed type is a research gap. Furthermore, recent modifications to the feed efficiency of maternal sheep may not have been updated in Ausfarm.

The dates for mating were selected Following producer engagement. The mid-point of mating in the spring models was November 7th, the summer mated model joined ewes on 17th January and the autumn models mated on March 14th.

4.1.1 Process of **model** development

The development and analysis of the AusFarm models included nine primary steps. The basis of each of the nine steps are detailed in Table 2.

Table 2. The steps taken to develop the AusFarm models

Step	Development process	No. models
1	Identify eight locations to be modelled	8
2	Validate cropping and pasture information	8
3	Develop three genotypes, incorporate for each location	24
4	Introduce three mating seasons at each location	72
5	Incorporate seasonal management practices	72
6	Produce iterations for 'high' and 'low' reproductive rates for each location, genotype	216
7	Produce iterations for 'high' and 'low' grain price for each location, genotype, joining season and reproductive rate	648
8	Determine optimum stocking rate for each model iteration	648
9	Analyse sheep production and gross margin outputs	648

4.1.2 Model description and validation

Model simulations were performed using AusFarm modelling software (version 1.5.3) (Moore *et al.* 2007). Flexible rules allowed the management system to allocate land to different crop and pasture sequences, including sowing, harvest and rotations. Similarly, the annual reproductive cycle of sheep, sale of lambs and cast for age animals and grazing management was also managed by flexible rules.

4.1.3 Locations, weather, soils and crops

Eight model locations were developed (Table 3). Climate data from The Long Paddock website (https://www.longpaddock.qld.gov.au/) was used for each location. Pasture growth rate curves are provided in the Supplementary materials (Supplementary Figures 1-8).

Table 3. Location of model simulations with corresponding rainfall. The Annual rainfall zone (mm) is that described for the period 1991 to 2020, by the Bureau of Meteorology (2022). Annual rainfall (mm) is the average annual rainfall reported from weather data information input into AusFarm simulation between years 1990 and 2020.

Location	Latitude and longitude	Annual rainfall zone (mm)	Annual rainfall (model output) (mm)
NSW			
Bookham, NSW	-34.8637, 148.6063	600-1000	743
Bungarby	-36.7482, 148.9837	400-600	536

Location	Latitude and longitude	Annual rainfall zone (mm)	Annual rainfall (model output) (mm)
Condobolin	-33.0892, 147.1471	400-600	446
Glen Innes	-29.7388, 151.7388	600-1000	808
Narrandera	-34.7470, 146.5526	400-600	403
Trangie	-32.0319, 147.9827	400-600	483
	VIC		
Hamilton	-37.7410, 142.0227	600-1000	616
	SA		
Keith	-36.0990, 140.3554	400-600	432

Each production system consists of a 2000 ha farm with 16 paddocks allocated to cropping and/or pasture production. At each location soil and pasture types, cropping and pasture rotations were identified through consultation with local experts and publications (Table 4). Where a location incorporated a cropping rotation, animals did not have access to the long fallow rotation but were able to access stubbles for grazing when present. Livestock had access to stubbles when groundcover was above 0.5 t/ha, for a maximum of 135 days and were removed when sufficient pasture was available. Each location also had three feedlots to allow separate feeding of mature ewes, maiden ewes and lambs when pasture thresh-holds fell below target. The cropping rotation and pasture growth at each location were validated against published data where possible, and in consultation with local experts. Grazing management rules are provided separately in the supplementary materials (Supplementary Table 1). Body condition score targets across the reproduction cycle were identified and are described in the supplementary materials (Supplementary Table 2).

Table 4. Soil, crop and pasture characteristics, rotation, and validation reference for each model location. At each location, land use sequences^a were employed, separated by a comma (,); P = permanent pasture, L = long fallow rotation, W = wheat crop rotation, B = barley crop rotation, C = canola crop rotation and A = annual clover.

Location	Soil type	Land use sequence	Crop area proportion	Pasture area proportion	Crop species	Pasture species	Validation reference
					NSW		
Bookham, NSW	Sandy to sandy loam	P,P	-	1.00	-	Microlaena, Sub clover (Seaton Park) and Annual Ryegrass	Soil: as per model developed in AusFarm by NSW DPI researcher Pasture: (Graham, 2017)
Bungarby	Basalt	P,P	-	1.00	-	Austrostipa spp., Poa sieberiana and Sub clover (Seaton Park)	Soil and pasture: (Moore, 2010)
Condobolin	Sandy loam over sand to light clay	PPPLWWBW, P	0.31	0.69	wheat, barley,	Sub clover (Dalkeith), Medic (paraggio), early annual grass	Soil: ApSoil: #690, used for region by NSW DPI researcher Pasture: EverGraze (central west slopes, http://www.evergraze.com.au/library-content/regional-pasture-growth-rates/index.html) and (Graham, 2017)
Glen Innes	Sandy clay-loam	P,P	-	1.00	-	Tall fescue, Austrodanthonia spp. and White clover	Soil: as per model developed in AusFarm by NSW DPI researcher Pasture: Local expert (NSW DPI researcher), EverGraze for Northern Tablelands of NSW: http://www.evergraze.com.au/library-content/regional-pasture-growth-rates/index.html): (Ayres, 1996; Graham, 2017)

Narrandera	Brown Chromosol	P,P	-	1.00	-	Austrostipa spp., Sub clover (Seaton park) and Annual Ryegrass	Soil: ApSoil # 174 Pasture: Outputs from former NSW DPI expert GrassGro model simulation
Trangie	Light over medium clay, sandy at depth	PPPLWWWB, P	0.31	0.69	wheat, barley,	Lucerne (winter active), Sub clover (Dalkeith) and annual grass	Soil: ApSoil # 683 (recommended by DPI NSW researchers) Pasture: DPI experts, EverGraze (central west slopes, http://www.evergraze.com.au/library-content/regional-pasture-growth-rates/index.html)and (Graham, 2017)
					VIC		
Hamilton	Sandy loam over clay	PPWBW, P, P	0.20	0.80	wheat, barley,	Lucerne, Perennial ryegrass, Sub clover (Leura) and Phalaris	Soil: ApSoil #632-YP Pasture: previous AusFarm model validated for area (Kennedy, 2016)
					SA		
Keith	Shallow sandy loam on calcrete	AAWCW, P, P	0.20	0.80	clover, wheat, canola,	Lucerne (semi winter active), annual grass, Sub clover (Leura) and Phalaris	Soil: ApSoil # 1246 (recommended by SARDI local expert) Pasture: (Graham, 2017)

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[a] Land use sequence: at each location simulated paddocks (n = 16) were rotated through a series or pasture or cropping rotations (if applicable), allowing land to be divided and used for a certain purpose in sequence.

Management dates for the ewe reproductive cycle were constant across locations (Table 5), with the practice of pre-mating supplementation to increase fertility and ovulation rates being the exception. Spring and autumn joined Composite ewe producers, by majority, did not practice flushing, but those joining during summer did and was captured in the development of the models. The majority of Maternal and Merino producers engaged the same flushing practices, respective of breed, across all seasons of joining. Note that the length of mating was 44 days. In AusFarm, a joining event occurs 10 days after the start of joining, and then every 17 days thereafter, therefore capturing three oestrus cycles, which was reported by majority of sheep producers (Bates et al., 2023).

Table 5. Management dates for each season and joining and ewe breed. Also included is sale events for respective breed, based on results from a producer survey (Bates *et al.* 2022b).

Management points	Summer	Autumn	Spring
Joining date	17-Jan	14-Mar	7-Nov
Pregnancy scan date	15-Apr	10-Jun	3-Feb
Late pregnancy date	30-May	25-Jul	20-Mar
Birth date	29-Jun	24-Aug	19-Apr
Wean date	27-Sep	22-Nov	18-Jul
Wean age (days from birth date)	90	90	90
First lamb sale date	1-Oct	1-Dec	1-Aug
Last lamb sale date	3-Apr	3-Jun	3-Feb
Target lamb sale weight (kg)	46	46	46
Composite pre-mating supplementation date	20-Dec	14-Feb	10-Oct
Composite pre-mating supplementation length (days)	28	0	0
Maternal pre-mating supplementation date	22-Nov	17-Jan	12-Sep
Maternal pre-mating supplementation length (days)	56	56	56
Merino pre-mating supplementation date	20-Dec	14-Feb	10-Oct
Merino pre-mating supplementation length (days)	28	28	28

The three breeds were modified using the breed standards in the AusFarm package (Table 6). Management practices varied between breeds and was informed by the producer survey (Bates et al., 2023). The reproductive performance for each genotype was derived using the field data (See Section 3.1). The real-world reproductive performance at a range of BCS was taken to be the base rate used in the reproduction parameter in the models (Table 7). The high and low pregnancy scanning percentages were then calculated as approximately ±20% of the mean for each breed and season of mating. Note that increases in fertility and pregnancy scanning rate (fetuses scanned per ewe mated) were limited as BCS increased from lean to fat, in accordance with the observations made from the field data.

Commodity values are reported separately in Appendices.

Table 6. Breed characteristics. The small and medium Merino genotypes were developed to suit the Merino production systems of different regions with different standard reference weights (SRW). Small Merinos were used at Bookham, Glen Innes and Hamilton, elsewhere the medium Merino was utilised.

	Composite	Maternal	Merino (small)	Merino (medium)
Genotype breed base	Dorset	Border Leicester x Merino	Small Merino	Medium Merino
Breed SRW (kg)	70	70	50	60
Mortality (%)	4	4	4	4
Weaner mortality (%)	4	4	4	4
Breed potential fleece weight (kg)	2.5	4	4.5	5
Max fibre diameter (micron)	27	27	19	20
Fleece yield (%)	70	70	70	70
Ram breed	Suffolk	Border Leicester	Small Merino	Medium Merino

Table 7. Model parameters adopted for adult ewe fertility (ewes pregnant per ewe mated) and pregnancy scanning rate (fetuses scanned per ewe mated) for Composite, Maternal and Merino breeds and presented for spring, summer and autumn, according to ewe body condition score (BCS).

		Spring				Summer				Autumn	
Reproductive level	High	Base	Low		High	Base	Low		High	Base	Low
Composite – Pregnancy rate											
BCS ≤ 2.5	91	89	85	BCS ≤ 2.5	95	90	82	BCS ≤ 2.5	96	92	88
BCS >2.5 ≤ 4	96	97	92	BCS >2.5 ≤ 4.5	97	94	88	BCS >2.5 ≤ 3	98	96	92
BCS > 4	95	93	88	BCS > 4.5	95	92	84	BCS > 3	98	95	91
Composite – Pregnancy scanning rate											
BCS ≤ 2.5	1.78	1.71	1.55	BCS ≤ 2.5	1.69	1.43	1.29	BCS ≤ 2.5	1.81	1.63	1.49
BCS >2.5 ≤ 4	1.89	1.84	1.67	BCS >2.5 ≤ 4.5	1.83	1.61	1.43	BCS >2.5 ≤ 3	1.87	1.75	1.59
BCS > 4	1.76	1.67	1.51	BCS > 4.5	1.82	1.63	1.47	BCS > 3	1.91	1.77	1.61
Maternal – Pregnancy rate											
BCS ≤ 3	78	71	67	BCS ≤ 2.5	90	85	81	BCS ≤ 2.5	85	77	73
BCS >3 ≤ 4	95	88	84	BCS >2.5 ≤ 3	94	88	83	BCS >2.5 ≤ 3	93	87	81
BCS > 4	91	87	82	BCS > 3	96	92	88	BCS > 3	86	83	79
Maternal – Pregnancy scanning rate											
BCS ≤ 3	1.34	1.14	0.98	BCS ≤ 2.5	1.43	1.28	1.08	BCS ≤ 2.5	1.50	1.30	1.14
BCS >3 ≤ 4	1.52	1.33	1.14	BCS >2.5 ≤ 3	1.61	1.44	1.24	BCS >2.5 ≤ 3	1.74	1.58	1.37
BCS > 4	1.63	1.46	1.28	BCS > 3	1.67	1.53	1.33	BCS > 3	1.58	1.50	1.26
Merino – Pregnancy rate											
BCS ≤ 2	90	89	85	BCS ≤ 2.5	82	80	77	BCS ≤ 2	95	91	87
BCS >2 ≤ 3.5	92	90	86	BCS >2.5 ≤ 4	88	86	82	BCS >2 ≤ 3	98	96	92
BCS > 3.5	84	82	77	BCS > 4	88	85	81	BCS > 3	98	95	93
Merino – Pregnancy scanning rate											

		Spring				Summer				Autumn	
BCS ≤ 2	1.35	1.25	1.05	BCS ≤ 2.5	1.29	1.16	0.96	BCS ≤ 2	1.47	1.28	1.08
BCS >2 ≤ 3.5	1.49	1.34	1.18	BCS >2.5 ≤ 4	1.48	1.33	1.12	BCS >2 ≤ 3	1.57	1.39	1.19
BCS > 3.5	1.26	1.12	0.88	BCS > 4	1.56	1.4	1.24	BCS > 3	1.62	1.49	1.29

4.1.4 Income and expenses

Income and expenses that inform the gross margins are based on the NSW Department of Primary Industries Sheep gross margins (April-September 2020; https://www.dpi.nsw.gov.au/agriculture/budgets/livestock).

Only income and expenses related to the sheep production enterprise were captured in the model outputs. If a location incorporated cropping as part of its management rotation, this was not captured in the gross margins output, and was only present to ensure animals could move between paddocks and graze stubble paddocks as indicated in the producer survey. Three grain prices were tested for their effect on profit, with the base price being $315/t, with 25% differences in prices tested, being $394/t for the high prices and $236/t based on the NSW Department of Primary Industries (2021) Sheep gross margins. A pasture maintenance value of $38/Ha was used across all simulations. Skin price for lambs and mature sheep, $4.52 and $5.26, respectively, were used based on data from Meat and Livestock Australia Limited (2022a, 2022b). The spring mated Composite flock used hormone manipulation (Regulin™)and as such a value of $7/head was used to account for this. Rams were used at a rate of 1.5% of the breeding ewe flock and 20% were replaced annually. The value of lamb meat, CFA ewes, replacement rams and wool were derived from the values used within the NSW Department of Primary Industries (2021) are presented in Appendix x (see above comments).

All models were run for the period 1991 to 2020. The first year of sheep and gross margin data was excluded from analysis to accommodate any anomalies associated with the model initialisation. Data for summer and autumn mated flocks was collected between 1990 and 2019, while spring flocks from 1990 to 2020 as the reproductive cycle finishes in the following year. This ensured 30 complete reproductive cycles were captured for each mating season explored.

4.1.5 The effect of increasing grain allowance

Grain feeding allowances were suggested by Warn *et al.* (2006) that allowed 30 kg/head of grain fed to all ewes in four out of ten years, however current grain and meat prices differ, suggesting that the allowance could be altered. The original feeding rule is defined in the present study as Low Grain Allowance (LGA). More recently, gross margins produced by the (NSW Department of Primary Industries 2021) increased the feed budget to 35 kg/head for Merino and 42 kg/head for Maternal ewes, the latter of which was also applied to the Composite ewe enterprises. The new supplementary feeding rule was established to be these amounts fed out in no more than four out of ten years for Merino and non- Merino ewes, respectively. This new rule is defined as High Grain Allowance in the present study (HGA).

4.1.6 Income and expenses

A detailed table of the top three expense items and income sources for each site for the base grain price models is provided in the appendices. The high grain price models and the low grain price models are also provided.

4.1.7 Analytical methods

Boxplots and scatterplots are presented for each location to graphically represent the variation observed in profit between the factors of season and breed. In previous milestone reports, linear mixed models were used to examine the variation over time and due to the factors. This analysis was used to interrogate the large amount of data created and multiple, interrelated variables such as reproduction and stocking rate. However, it is contrived to analyse outputs that are pre-determined parameters defined in the construction of the model itself, such as reproduction rate. The advice received from CSIRO farm system modellers was to pursue the Conditional Variation at Risk.

Conditional Value at Risk

A financial calculation for risk is made using Conditional Value at Risk (CVaR), which examines the mean annual gross margin for the lowest 20% of gross margins. The CVaR is a measure of riskiness and enables a financial comparison between the experiments tested within each location, for each breed, season of mating, reproduction rate and grain price. A risk-averse producer, when all else is equal, is likely to prefer a high CVaR because it is a measure of downside risk and is defined in terms with meaningful units easily understood by the reader. A higher average gross margin in the bottom 20% of years indicates less financial risk.

When comparisons of CVaR are being made at a constant grain price, then the production risks are being evaluated, whereas when comparing CVaR with grain price variation, comparisons should be made at a constant level of reproduction to evaluate the effect of grain price variation on risk.
The use of CVaR in application to AusFarm model outputs are reported by Moore (2014) when examining perennial grasses in systems, or by Smith and Moore (2020) when considering the season when lucerne stands are terminated and effects on whole farm profit.

5. Conclusions

5.1 Key findings

5.1.1 Reproduction responsiveness

Data collected from 29,125 pregnancy scanned ewes examined relationships between pre-mating liveweight and body condition score with the reproduction outcomes. All ewes were mixed aged and had lambed previously. In total 59 flocks were engaged in the research and were mated in one of three seasons: spring, summer or autumn. The ewe breeds reflected the modern mix available to Australian sheep producers and included Composite, Maternal, Merino or shedding hair breeds.

Mean pregnancy scanning rate was high at 150.1 ± 70.4%, with Composite ewes recording very high rates overall (Table 10). The scanning rate for the Shedder ewes should be considered to be low, given the result for Merino ewes. Pregnancy scanning rate was improved by liveweight, body condition score, season and breed.

Several important relationships were observed between fertility or litter size with liveweight, BCS and season of mating. First, this study shows that for all seasons of mating, fertility and litter size are higher in ewes with higher pre-mating weight or BCS. Little literature can be found that reports the relationships between weight or BCS and season. Second, the testing of linearity by including quadratic terms for liveweight and BCS demonstrated the model improved with their inclusion. This is an important finding and deviates from existing extension messages, where graphics are linear. The finding shows both fertility and scanning rate are curved responses to liveweight and BCS, which decline at higher BCS/LW. Third, the reproduction response curves differ between breeds and season of mating. Finally, the survey of 59 flocks showed reductions in scanning rate as ram mating percentage increased. This latter point was unexpected and may require further investigation.

5.1.1.1 Composite

Fertility was lower in heavy (90+ kg) Composite ewes, while there was no difference in fertility between the 60, 70 and 80 kg classes. The optimal weight for mating and peak fertility was 70 kg for Composite ewes. There was minimal response in fertility across the observed range in ewe BCS. This may be a result of the generally favourable conditions observed across south-eastern Australia during the study but appears to be characteristic of the Composite sheep because responses to BCS were observed in the other breeds. The effects of season appear to change the response to weight, as fertility declines were observed when LW exceeded 75 kg. Litter size also decreased as ewe liveweight increased, where a sensible target weight might be 60 kg to 75 kg. A target BCS for optimal litter size appears to be 3.5 to 4.0.

5.1.1.2 Maternal

Fertility increased in Maternal ewes as the weight class increased from ≤50 kg to 70 kg then plateaued between 70-90 kg; thus 70 kg appears to be a sensible target weight for optimal fertility. There was a clear limitation in BCS as well, where fertility increased up to 3.0 to 3.25 BCS, but not thereafter. Litter size in Maternal ewes improved up to 70 kg, although small numerical increases occurred to 90+ kg. Similarly, litter size was not higher in ewes that were heavier in condition than 3.0 to 3.25, although the highest scanning rate was observed in ewes 3.5 to 3.75 score and decreases were observed at condition scores exceeding this. Maternal ewes appear to have an optimal weight for reproduction around 70 kg and BCS 3.0 to 3.25.

5.1.1.3 Merino

Fertility in Merino ewes increased up to 60 kg where it peaked. While there was no difference in fertility between 60 and 70 kg ewes, there was a numerical decrease in ewes ≥70 kg. Fertility in Merino ewes appeared to be relatively insensitive to body condition score changes where there was no difference between lean (≤2.25) and 3.5 to 3.75 BCS, there were reductions in fertility in ewes more forward than ≥4.0. The curvilinear polynomial plots demonstrate the relationship more clearly, showing improvements in fertility as BCS increased and after BCS 3.5, the gains became losses. Litter size in Merino ewes improved as liveweight increased to 70 kg and decreased thereafter and litter size peaked at ewe BCS 3.5 to 3.75 and fatter ewes had lower litter size. Merino ewes had the highest fertility and litter size when around 60 to 70 kg liveweight and BCS around 3.5 BCS.

5.1.1.4 Shedder

Caution is advised when interpreting the Shedder responsiveness due to the small number of flocks. There was an increase in fertility as the weight class increased to 70 kg, but there was no difference in heavier ewes. More forward conditioned ewes had the highest fertility and may be a characteristic of the breed, peaking in ewes 4.0 to 4.25. Litter size increased to 70 kg and did not improve thereafter and peaked in ewes BCS 4.0 to 4.25. A target weight for Shedder ewes appears to be 70 kg, at BCS 4.0 to 4.25.

5.1.1.5 Trivariate responsiveness

The analysis of fertility and litter size showed concurrent interactions between liveweight and BCS. Among most flocks there were different types of response, but generally, high BCS in light weight ewes, or low BCS in heavy weight ewes resulted in higher fertility. This relationship was observed in autumn- and summer-mated Maternal, spring-,summer- and autumn-mated Merino and autumn-mated Shedders. The exceptions are Composite flocks, where lower liveweight was a dominant factor in improving fertility.

The probability of having multiple pregnancies became less sensitive to BCS when liveweight was around 60-70 kg. It is clear from Figures 27 to 29 that there are some flocks that respond little to improvements in BCS and liveweight.

5.1.2 Profitability

Farm system models were established for eight locations in southern Australia, including six sites in NSW (Bookham, Bungarby, Condobolin, Glen Innes, Narrandera and Trangie), one site in Victoria (Hamilton) and one site in South Australia (Keith). Three sheep breeds (Composite, Maternal and Merino) were modelled to examine the effects on profitability ($/Ha) when examining different rates of reproduction, grain and season of mating. Mating scenarios included spring, summer and autumn. Final models were optimised to maximise profit, via modification of stocking rate to meet rules for the maintenance of groundcover and avoid the overuse of grain feeding. Reproduction parameters were determined using the field study's fertility and pregnancy scanning results at a range of BCS, for each breed and season of mating. Scenarios for higher and lower reproduction rates were created by adjusting the mean scanning rate ±20%. The scale of the changes varied between breeds and season of mating. The impact of grain price was also examined, with differences of 25% above and below the Base grain price ($315/t). Containment systems were included in all farm systems, allowing stocking rate to remain higher overall, used according to growth rate and pasture groundcover rules. Ewe lambs were mated in the Composite and Maternal farm systems. Maternal ewes were replaced when cast for age, while the Composite and Merino flocks were self-replacing.

With 81 variables within each site (3 breeds, 3 seasons, 3 reproduction rates and 3 grain prices), it is difficult to succinctly identify the key findings for each of the eight sites. The detail for each site describing the more or less profitable season of mating, for each breed, and the effect of reproduction and grain price is provided in appendices to this report.

Early modelling included hair (shedding) sheep breeds but it was clear the models were not responding appropriately for the animal type, subsequently this breed was not included in further modelling.

5.1.3 Grain allowance rule

Grain feeding allowances recommended by Warn *et al.* (2006) allowed 30 kg/head of grain fed to all ewes in four out of ten years. More recently, gross margins produced by the (NSW Department of Primary Industries 2021) increased the feed budget to 35 kg/head for Merino and 42 kg/head for Maternal ewes. The new high grain allowance (HGA) rule was included and, in line with the previous recommendation, these amounts were fed out in no more than four out of ten years. Preliminary results were encouraging, and the rule was accepted for all models.

5.2 Benefits to industry

- This study has created reproduction response curves for liveweight and body condition score for four Australia sheep breed types, across three seasons of mating.
- Reproduction response curves for fertility and scanning rate demonstrate limiting returns for heavier liveweight ewes and ewes in heavier in body condition.
- The response curves for fertility and scanning rate have been demonstrated across seasons and the relationship generally differs between breeds and seasons.
- Producers need to be aware of the limiting gains when increasing ewe weight or body condition beyond the identified optimums for each breed and season. Producers should investigate and understand those relationships within their own flock. To support producers, collect, collate and analyse their ewe data, training resources should be created. The method can be easily adopted into the LTEM or Towards 90 training packages. Producers require EID, pre-mating LWT, BCS and scanning results for pregnancy status (0,1) and litter size (0,1,2). The data can be easily collated in Microsoft Excel™ and pivot tables created for mean pregnancy or litter size outcomes, tabulated with either LWT or BCS. A scatterplot should be created with regression lines fitted and tested for best fit using linear or polynomial functions. A response calculator, developed by NSW DPI, was previously available online, but the fitted lines were linear and thus may be misleading and require modification.

6. Future research and recommendations

- Farm system modelling of hair breeds (shedders) has constraints resulting unreliable results. The true composite (multi-breed hybrids) and hair sheep are genotypes not fully supported by the GrazPlan packages. Substantial amounts of work are required to create sufficient data for the development and inclusion of new equations for these breeds into the decision support packages.
- This project has identified low fertility and low scanning rates associated with the Shedder breed and this requires further research. Unpublished data from a large-scale pregnancy scanning database suggests lower fertility is common for shedding sheep in Australia (Prof. Simon de Graaf, *pers. comm.*). The nature of this animal, well suited to arid production zones, is suited to low input farming systems and rangelands. There is a tendency for continuous mating, which makes a single pregnancy scan difficult to interpret, but also increase the risk of infectious reproductive disease, such as brucellosis. Accelerated lambing systems, such as lambing three times in two years, or in some locations, lambing twice each year, are common in higher rainfall environments, which means interpretation from a single pregnancy scanning event is difficult. Capturing data that fairly represents the breed requires investigations to occur within flock over multiple mating cycles, using multiple flocks located in high and low rainfall environments.
- Development of a Microsoft Excel software program to produce response curves for individual producers would be helpful in establishing BCS and liveweight targets within a flock.
- Spring-mated composite flocks were difficult to find. Consequently, caution is required when extrapolating the results for that breed, when mated in spring. Nevertheless, the results are real for the highly fecund flock that used Regulin® and pointed to high profitability. To understand the reproduction potential of that breed, when mated in spring requires further data collection, of the same nature as the present study.

- The relationship with ram per cent was unexpected and inconsistent with published literature. Given the observational (non-experimental) nature of this study, this finding should be considered cautiously by the wider red meat industry. It is recommended that further investigation into ram percentages be undertaken.

7. Acknowledgements

The delivery of the field work was not possible without the meticulous and tireless field work delivered by Ms Jackie Chapman and the generous support of the sheep producers across New South Wales, Victoria and South Australia.

8. Publications

Two peer-reviewed papers have been published as a result of the funding from this work, Bates et al. (2022b, 2023), and two conference abstracts were published (Bates et al., 2021, 2022a).

Draft manuscripts for peer-review publication have been prepared for the Grain Allowance study and the major findings examining reproduction and grain price variations and their effects on profitability and riskiness.

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