Genetic parameters of body condition score (BCS) and effects of BCS and BCS change on ewe performance

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Abstract

Body condition score (BCS) is an important management technique that can be easily learnt and implemented on farm to determine the body condition of ewes. The industry recommended BCS is 3.0 to 3.5 at mating to ensure optimal production. Currently the average industry BCS is less than 3.0 and recent research suggests that the change in BCS may be more important for determining the subsequent production of the ewe. The objectives of this thesis were to examine the relationships between BCS and production through exploring the effects of genetic and phenotypic BCS and BCS change on productive performance.

Records of BCS were obtained from Focus Genetics and New Zealand Merino flocks to determine the effect of BCS change on phenotypic production and estimate the genetic parameters of BCS. There was no increase in production for ewes above a BCS of 3.5, therefore, BCS of 3.0 to 3.5 should remain the target BCS for phenotypic production. Ewes that decreased phenotypic BCS between lambing and weaning were associated with greater production indicating these ewes had utilised their stored body fat to achieve high milk yields. The estimated heritabilities of BCS change were low indicating limitations in the ability to alter the shape of BCS profiles by selection.

Heritability, genetic and phenotypic parameter estimations of BCS and production traits were performed on 9,585 dual-purpose ewes and 2,007 Merino ewes. The heritability of BCS in New Zealand dual-purpose sheep was found to be moderately heritable (0.16-0.30) and had a high genetic correlation between BCS measurements across the production year. The best time to record BCS for genetic selection was confirmed to be mating.

Live weight and BCS are highly genetically correlated, therefore, it may be relevant to explore the inclusion of BCS in the selection criterion to ensure that BCS does not exceed the optimal range of 3.0 to 3.5. The results of this thesis indicate that observing BCS is a valuable tool and it would be possible to change the genetic potential for BCS with genetic selection. This information can be used to develop selection criteria for BCS.

Declarations

I, Isabel May Vialoux (nee Tait), declare that this thesis contains no material that has been accepted for a degree or diploma by the University or any other institution. To the best of my knowledge no material previously published or written by another person has been used, except where due acknowledgement has been made in text.

This thesis was written so that the chapters can be easily formatted for publication. Therefore, each chapter contains a full discussion and the overall general discussion (Chapter 8) provides a concise summary of the entire thesis content. The references from each chapter are combined and presented at the end of the thesis.

Acknowledgements

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Most of all, to my husband Andrew, for grammar checking my writing even when you have no idea what it means. I know this journey hasn't been easy, so thank you for all your support and I am looking forward to the next chapter of our lives!

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AFL	Age at first lambing
AIC	Akaike information criterion
AOD	Age of dam
avWWT	Average lamb weaning weight per ewe
BCS	Body condition score
ΔBCS	Body condition score change
BV	Breeding value
EBV	Estimated breeding value
FW12	Fleece weight at 12 months of age
LSM	Least squares mean
LW	Live weight
LW6	Live weight at six months
LW8	Live weight at eight months
LW12	Live weight at 12 months
NLS	Number of lambs scanned
NLB	Number of lambs born
NLW	Number of lambs weaned
RPE	Relative prediction error
RRM	Random regression model
SIL	Sheep Improvement Limited
TLW	Total litter weaning weight
WWT	Weaning weight at approximately 3 months of age
WWT_m	Maternal weaning weight

1 General Introduction

The New Zealand sheep industry is primarily reliant on pasture supply to meet the energy demands of the ewe. During late pregnancy and lactation when rearing two or more lambs (Sorensen et al. 2002), the energy demand on the ewe is high (Chilliard et al. 2000). This high energy demand can cause the ewe to be in a period of negative energy balance where energy demands are greater than feed intake. During this period of negative energy balance the ewe uses body fat to meet the energy requirements of milk production (Banchero et al. 2004; Cannas 2004). The body condition score (BCS) technique is used on-farm to assess the body fat level of the ewe (Kenyon et al. 2014).

Body condition score in breeding sheep has been documented as having an effect on phenotypic productive performance (Kenyon et al. 2014), however, to date BCS has only been considered as a single point in time and in terms of the effect this has on the subsequent production of the breeding ewe. The fat reserves of the animal fluctuate throughout the year, and thus BCS changes (Macé et al. 2018a; Mace et al. 2018b). These fluctuations are heavily dependent on the feed supply and feed quality. The BCS change between individual BCS measurements has not been well documented and there is only one international study documenting how BCS changes across the production cycle of the breeding ewe (Macé et al. 2019). The changes across the production cycle would illustrate the different BCS changes throughout the year and could be used to get a clearer picture of how this influences productive performance. The BCS across the production year and the production of the ewe could provide value in identifying the breeding ewes that are potentially more efficient than others.

On a genetic level, BCS at mating has been recorded in the national New Zealand sheep industry's performance recording and genetic evaluation database from 2015 (Sheep Improvement Limited 2016b). It was recommended by Sheep Improvement Limited (SIL) that BCS was recorded at mating or weaning (Sheep Improvement Limited 2016b). The BCS breeding value is not included in the New Zealand maternal worth index (NZMW) used for evaluating dual-purpose sheep and there are limited New Zealand studies that report the genetic correlations between BCS and production traits (Everett-Hincks and Cullen 2009). It is important to know the genetic correlations before imposing selection pressure on a trait to ensure there are no unfavourable outcomes in doing so.

Shackell et al. (2011) has previously reported a high genetic correlation between BCS and live weight of New Zealand sheep. There is currently a negative economic weighting on live weight in the NZMW (Byrne et al. 2012; Sheep Improvement Limited 2019c), however, the genetic trend for live weight remains positive (Sheep Improvement Limited 2019a). The high genetic correlation between live weight and BCS means that selecting against live weight could slow genetic gain for BCS. Unlike live weight, BCS is an optimum trait where a BCS between 3.0 to 3.5 is desirable and low and high BCS values are undesirable. Therefore, it is important that BCS is considered as a separate trait. The general aim of this thesis was to investigate the effects of the genetic and phenotypic BCS and BCS change on ewe productive performance.

The main objectives of this thesis are to:

a) Describe the relationships between BCS, change in BCS and production traits in sheep to establish a better understanding of the influence of BCS on productive performance.
b) Determine the genetic parameters of BCS, BCS change and production traits.
c) Identify and characterise BCS profiles in a population of ewes.
d) Evaluate the effects of phenotypic BCS profiles on sheep production.
e) Determine the genetic variances of BCS across the production year.

All analyses undertaken in this thesis were completed retrospectively using historical industry data sets. Two data sets were made available for analysis including the New Zealand Merino central progeny test data and Focus Genetics flocks. Chapter 4 was completed using New Zealand Merino central progeny test data. Chapter 5 utilised all the Focus Genetics nucleus flocks including Goudies, Freestone, Waipuna and Pohuetai. Only the Freestone flock was used for analysis in Chapters 3, 6 & 7.

2 Review of literature: nutritional and genetic effects on body condition score.

2.1 Introduction to body condition score as a technique

The New Zealand sheep flock has been in continual decline since a peak of 57 million ewes in 1990 (Beef+Lamb New Zealand 2018). It stood at 27.2 million ewes in 2017 which was distributed evenly between the North and South Islands (Beef+Lamb New Zealand 2018). However, individual production levels have increased from a lambing percentage of 100% and an average lamb carcass weight of 13.9 kg in 1990 to an average lambing percentage of 130% with an 18.6 kg average lamb carcass weight in 2017 (Beef+Lamb New Zealand 2018). This has been achieved through a number of management changes including breeding for increased reproductive performance, selection for increased lamb growth rates, breeding at a younger age and improved nutrition (Morris and Kenyon 2014).

Production of the ewe is influenced by its body reserves (see review by Kenyon et al. 2014). This can be estimated through two measures, either live weight and/or body condition score (BCS). Live weight is simple to measure but does not directly represent body reserves of an animal (Russel et al. 1969; Herd and Sprott 1986; Corah 1989; West et al. 1990; Dunn and Moss 1992; Kunkle et al. 1994). Live weight can be influenced by gut fill, pregnancy status (Herd and Sprott 1986), age, breed, stature and wool (Kenyon et al. 2014). While these factors affect live weight, they do not necessarily influence the body reserves of the animal. Therefore, live weight, is an inaccurate measure of nutritional status due to these variations (Kenyon et al. 2014). It has been suggested that BCS is a better indicator of body reserves than live weight (Russel et al. 1969; Herd and Sprott 1986; Corah 1989; Dunn and Moss 1992; Bocquier et al. 1999). The BCS technique was first developed in the 1960s (Jefferies 1961). It has been suggested feed management decisions such as offering ewes more or less feed, should be based on BCS, rather than live weight (Dechow et al. 2001).

Body condition score as commonly practised is a subjective estimate of both the level of subcutaneous fat and muscle on the ewe (Corah 1989; Sanson et al. 1993; Thompson and Meyer 1994; Burkholder 2000; Van Burgel et al. 2011; Kenyon et al. 2014) and is used to determine the current level of animal body reserves (Wagner et al. 1988; Corah 1989; Bishop et al. 1994; Kunkle et al. 1994). The original purpose of the BCS technique proposed by Jefferies (1961) was; to control the nutrition levels of sheep so feed supplies were managed efficiently, to detect small differences in condition not noticeable by the outside appearance as it is obstructed by wool cover, and to allow farmers to be aware of major losses (ie. one BCS change over 2-3 months) of ewe condition by tracking the change in BCS over time. Body condition score has also been shown to be positively related to many production traits (Kenyon et al. 2014 and see later sections). The technique requires no specialised equipment, and therefore, can be learnt by farmers and implemented on farm (Kenyon et al. 2014).

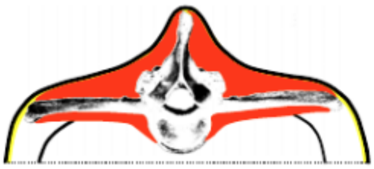
Knowledge of the use and benefits of the BCS technique for management decisions and benefits gained have been transferred to farmers, but not all farmers appear to actually actively implement the BCS technique as a management tool. A 2012 survey showed that less than half (43%) of sheep farmers in New Zealand had used the BCS technique on farm in the previous three years (Corner-Thomas et al. 2015b). In that study, a greater percentage of farmers were found to use the BCS technique if they had a level of education greater than high school, such as at the certificate, diploma or degree level. Conversely, as farmer age increased, the likelihood of using the BCS technique decreased. An Australian survey in 2008 found that only 38% of Australian sheep farmers were aware of the use of the BCS technique and a lower proportion (21%) actually used BCS as a measure of whether they were meeting nutritional targets at key times of the year (Curnow et al. 2011). It is concerning that less than half of sheep farmers in New Zealand and Australia use the BCS technique (Curnow et al. 2011; Casey et al. 2013; Corner-Thomas et al. 2013). It is important that industry professionals such as consultants or those in extension roles can demonstrate to farmers the benefits of the BCS technique. In Australia, 94% of industry professionals were aware of BCS which shows that knowledge of the available research was widespread, however, only 55% of these professionals had actually practically put it to use on farm (Curnow et al. 2011; Jones et al. 2011). Therefore, if BCS is to be used as a farm management tool, farmers must first be taught the technique and then be shown the benefits of utilising it. In The Australian Lifetime Ewe Management program, reported that farmers were better able to maintain individual ewes at a BCS within a target range (4% to 94%; Trompf et al. 2011). This indicates, that with appropriate education and hands on training, there is scope for increasing the number of farmers utilising the phenotypic BCS measurement and able to receive the benefits that are associated with it.

There is scope for sheep BCS implementation to increase and be used to change BCS on farm. The aim of this chapter is to review the literature on BCS in sheep, BCS changes across the year and the genetic and phenotypic relationships between ewe BCS and various production traits. It also identifies where there is a current lack of knowledge in regards to BCS.

2.2 Body condition score measurement technique

The BCS scale varies between countries and species, however, low values refer to lower amounts of soft tissue cover (fat and muscle), while high values are associated with greater cover (Russel et al. 1969; Roche et al. 2009; Kenyon et al. 2014). The most common BCS scale is a 1-5 scale (Jefferies 1961; Shands et al. 2009), including half units. In some cases, BCS has been measured in quarter units (Van Burgel et al. 2011). Table 2.1 describes the differences between BCS from 1 through to 5. Body condition score is assessed by palpating the spinous process (spine) and transverse processes (short ribs) processes, or protrusions of bone, in the loin area immediately behind the last rib which is the 13th rib (Table 2.1, Russel et al. 1969; Russel 1984a). Using the balls of the fingers and thumb, the soft tissue around the spine is felt by the thumb while the short ribs are felt by the fingers (Russel 1984). As an alternative, visual assessment of BCS can be undertaken, but this is only recommended within six weeks of shearing (Kenyon et al. 2014).

Table 2.1. Ewe body condition score scale 1-5 description and cross section of the measurement site for each score (reproduced from Kenyon et al. 2014).

Grade	Description	Illustration
Score 1	The spinous processes are prominent and sharp. The transverse processes are also sharp, with fingers passing easily under the end of this process. The eye muscle areas are shallow with little to no fat cover.	
Score 2	The spinous processes are smooth but still prominent. The individual processes can still be felt but only as fine corrugations. The transverse processes are smooth and rounded. However, it is still possible to pass the fingers under the ends of the processes with some pressure. The eye muscle areas are of moderate depth, but have sparse fat cover.	
Score 3	The spinous processes are smooth and rounded, and individual bones can only be felt with some pressure applied. The transverse processes are also smooth and are well covered. Firm pressure is required to feel over the ends. Eye muscle area is full and covered by a moderate degree of fat.	
Score 4	With pressure applied, the spinous processes can just be detected, although the ends of the transverse processes cannot. Eye muscle areas are full with a thick covering of fat.	
Score 5	Even with firm pressure applied, the spinous processes cannot be detected. Due to a high level of fat adjacent to the spinous process, a depression directly above where the spinous processes would normally be felt may be present. It is not possible to detect the transverse processes. The eye muscle areas are very full with very thick fat cover. It is possible to have significant deposits of fat cover over the rump and tail.	

2.3 Repeatability/reproducibility of body condition score technique within and between assessors

Repeatability measures the variation in multiple measurements taken by a single person under the same conditions. Effectively, one person should be able to measure the same BCS repeatably on the same ewe on the same day (Calavas et al. 1998; Bartlett and Frost 2008). Calavas et al. (1998) defined reproducibility as a measure of whether the same measurements can be reproduced at another time or by another person. It is useful to measure both repeatability and reproducibility to ensure that the BCS measured can be consistent across the industry and between farms.

Table 2.2 presents repeatability and reproducibility measures in terms of correlation between the repeated measures. Repeatability and reproducibility have been somewhat inconsistent across studies (Table 2.2). Yates and Gleeson (1975) reported a poor repeatability with inexperienced assessors. Inexperienced assessors can have difficulty achieving consistency which is why it has been suggested that repeatability increases with operator experience (Everitt 1962; Kenyon et al. 2014; Keinprecht et al. 2016). Reproducibility between inexperienced assessors have also been shown to have a low reproducibility (Yates and Gleeson 1975). Experienced operators, on the other hand, regularly have high levels of repeatability and reproducibility (Teixeira et al. 1989; Van Burgel et al. 2011; Phythian et al. 2012). Reproducibility between assessors was also found to be moderate to high (Shands et al. 2009; Keinprecht et al. 2016). Therefore, it is recommended that farmers assessing BCS on farm need to have some form of training to increase both repeatability and reproducibility. It is advised that at least one farm worker have some experience in the BCS technique and that for consistency, the same person measures BCS on the animals over time, however, this would not be necessary if there was high reproducibility between assessors.

Table 2.2. Reproducibility (between assessors) and repeatability (within assessors) of the sheep body condition score (BCS) technique (adapted from Kenyon et al. 2014).

Reference	Scale system used and smallest unit	Assessor experience level[b]	Reproducibility between assessors	Repeatability within assessors
(Everitt 1962)	1-10, whole units	Inexperienced	Variation between and within assessor over time, values not stated	
Russel et al. (1969)	0-5, 0.25 units	Not stated	>70% absolute agreement, <20% differed by 0.5 BCS units and <10% by 1.0	>80%, <15% of observations varied by 0.5 BCS units and <5% by 1.0 units
Milligan and Broadbent (1974)	0-5, units not stated	Not stated		r = 0.49-0.67
Yates and Gleeson (1975)	0-5, 0.25 units	Inexperienced	r_a = 0.05-0.27	r = 0.16-0.44
Evans (1978)	0-5, 0.5 units	Not stated	r = 0.81	r = 0.88
Teixeira et al. (1989)	0-5, 0.25 units	Experienced	80%	90%
Calavas et al. (1998)	0-5, 0.25 units			r = 0.6-1.0
Shands et al. (2009)	0-5, 0.25,0.5 units	Mixed skill	r = 0.73-0.89	r = 0.64-0.84
Van Burgel et al. (2011)	0-5, 0.25, 0.5 units	Experienced		0.2 unit difference in BCS mean of animals tested between assessments
Phythian et al. (2012)	0-5, 1.0 and 0.5 units	Experienced	r = 0.4-0.6	r = 0.6-0.7
Keinprecht et al. (2016)	1-5, whole units	Mixed skill	r = 0.44-0.80	

[a] r = correlation between assessments of BCS
[b] No experience = No sheep handling experience and no knowledge of BCS,
Inexperienced = Has handled sheep and some knowledge of BCS,
Experienced = Regularly performed BCS within the year prior to the study.

2.4 Body condition score correlations with liveweight, fat depth and total body fat

2.4.1 Live weight and body condition score

Live weight is not the preferred method of measuring body reserves. However, there are useful inferences that can be gained by comparing it with BCS. An animal's liveweight is made up of skeletal size, amount of muscle and fat on the body, physiological state (pregnancy and litter size), the length and wetness of the fleece and gut fill (Ducker and Boyd 1977). Therefore, as previously stated, a limitation of the use of live weight as a measure of assessing the ewe's nutritional status alone is that there can be frequent fluctuations.

Variation exists in the phenotypic relationship between BCS and live weight depending on breed and physiological state of the ewe (Table 2.3). When considering the linear regression between ewe live weight and BCS, Morel et al. (2016) reported that each whole unit (1.0) increase in BCS over the range 1.5 to 4.5, required a 7.7 kg increase in live weight, supporting the linear relationship reported by others (Table 2.3). Although Teixeira et al. (1989) reported a curvilinear relationship such that for every increase in BCS score, a greater live weight change was required (Table 2.3). An increase from BCS of 2 to 3, required a live weight increase of 10 kg, however, an increase from BCS 4 to 5 required a live weight increase of 16 kg. Regardless of a linear or curvilinear relationship with a breed, these combined results indicate that changes in live weight can be used as a guide for increasing or decreasing a unit of BCS.

Table 2.3. Reported change required in live weight per unit of body condition score (BCS) across various sheep breeds and classes (adapted from Kenyon et al. 2014).

Reference	Timing of measurement	Breed	Live weight change per unit of BCS (kg)
Jefferies (1961)			6.8
Russel et al. (1969)			10.6
Geisler and Fenlon (1979)	Mating	Eight breeds	3.3[a]-7.8[b]
Hossamo et al. (1986)	Mating	Awassi	5.8
Teixeira et al. (1989)	Dry	Rasa Aragonesa	7.0[a]-16.0[b]
Sanson et al. (1993)			5.1
Frutos et al. (1997)	Dry	Churra ewes	5.6
Kenyon et al. (2004a)	Mating	Romney	7.3
Kenyon et al. (2004b)	Mating	Romney	7.9
Kenyon et al. (2004b)	Mating	Romney composite	4.8
Freer et al. (2007)	Dry	Polwarth x SA Merino	6.3
	Dry (maiden)	Polwarth x SA Merino	7.3
	Dry	Saxon Merino	5.6
	Dry (maiden)	Saxon Merino	7.0
	Lactating	SA Merino	5.0
	Lactating	Saxon Merino	5.5
	Wethers	Saxon Merino	7.0[a], 10.0[b]
	Weaners	Saxon Merino	9.3
	Weaners		7.0
Sezenler et al. (2011a)	Mating	Kivircik, Sakiz and	7.0
	Lambing	Gokceada	6.8
	Weaning		7.1
Van Burgel et al. (2011)	Ewes	Merino	9.2
Vatankhah et al. (2012)	Mating	Lori-Bakhtiari	3.1
Ptáček et al. (2014)	Mating and Weaning	Suffolk	7.8
Benchohra and Amara (2016)	Lambing	Rembi	4.6[a], 8.5[b]
Karakuş and Atmaca (2016)	Lambing	Norduz	4.5
Morel et al. (2016)	Ewes	Romney cross	7.7
Average			**7.0**

[a] light ewes, ~50kg
[b] heavy ewes, ~70kg

2.4.2 Fat and body condition score

While generally it has been found that there is a linear relationship between live weight and BCS, there may be a non-linear relationship between BCS and the energy required to gain BCS. An increase in BCS at a higher starting BCS requires more energy to gain a unit in BCS, due to a greater proportion of this gain being fat rather than lean tissue (Zygoyiannis et al. 1997; Freer et al. 2007; Morel et al. 2016). Figure

2.1 below shows the partitioning of total metabolisable energy intake into energy used for maintenance, energy retained and energy lost as heat. The energy retained increases up to a BCS of 3.5 (black in graph) and then is constant at greater BCS values. The energy lost as heat increases substantially for each increase in BCS (dark grey in graph) and the energy for maintenance (light grey in graph) increases at a similar rate. As BCS increases, less of the metabolisable energy intake is retained in the body and more is lost in the form of heat production. These three factors combined results in a greater intake of energy required for a ewe with a higher BCS ewe to gain additional condition. From an efficiency perspective there is little advantage in gaining BCS above a BCS of 3.5 (Morel et al. 2016).

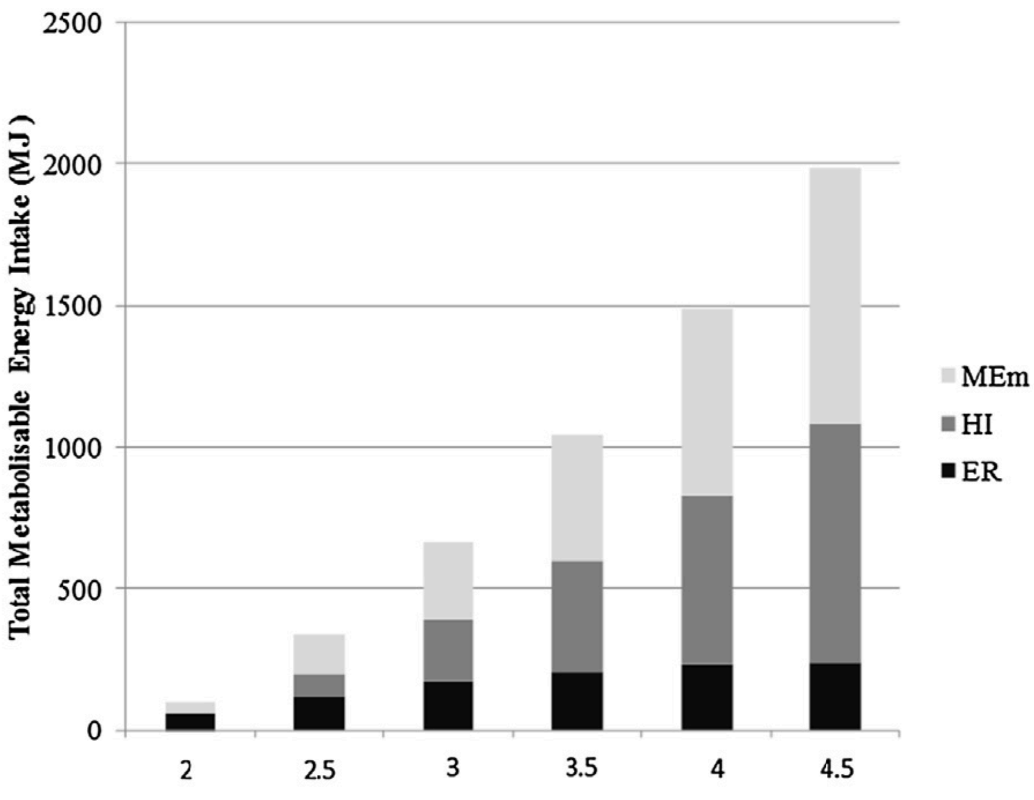


Figure 2.1. Partitioning of total metabolisable energy intake (MEi) between energy for maintenance (MEm), energy retained (ER) and heat increment (HI) at different mature ewe body condition scores (BCS, reproduced from Morel et al. 2016).

The total fat of the ewe can be difficult to assess without specific equipment or body dissection, however, it can be estimated using a range of traits as indirect measures. Ewe BCS has been reported to be a better estimate of total body fat than live weight (Russel et al. 1969; Yates and Gleeson 1975; Teixeira et al. 1989; Sanson et al. 1993). The partitioning of different fat deposits through the BCS range (1.5 to 4.5) was reported in Rasa Aragonesa sheep breed (Teixeira et al. 1989). In general, as BCS increases, subcutaneous fat and intermuscular fat increases substantially, while the visceral fat remains relatively constant as a percentage of fat. This relationship was confirmed in a study by Morel et al. (2016) who reported an exponential increase in total fat levels resulting in greater concentrations of energy stored as fat in the higher BCS ewes compared to lower BCS ewes (Morel et al. 2016).

The correlation between BCS and subcutaneous fat measured in slaughtered animals has been reported to range between 0.77 to 0.94 (Delfa et al. 1989; Teixeira et al. 1989; Sanson et al. 1993; Frutos et al. 1997). There is a positive linear regression between subcutaneous fat and internal fat in Romney and Romney composite breeds (Kirton and Johnson 1979), therefore, a change in subcutaneous fat is an indicator of increased total body fat. However, Frutos et al. (1997) reported that the Churra breed might differ from other breeds because it has been selected for milk production. Dairy breeds often partition more fat around the internal organs compared with that of dual-purpose Romney and Coopworth breeds (Frutos et al. 1997). This might suggest that BCS may not be the best measure of total fat in breeds selected for milk production. Nevertheless, in non-sheep milking breeds, BCS can be an indirect measure of total fat levels.

2.5 The basic physiology of fat

Adipose tissue stores energy (Christie 1978) and will herein be referred to as 'body fat' in this literature review, as that is the predominant industry term. Storing energy as body fat is more efficient on a weight basis compared to storing carbohydrates and protein (Germann and Stanfield 2002). This is due to the glycogen in carbohydrates and protein containing 75% water, whereas, triacylglycerols in fat are energy dense, containing almost no water (Vernon and

Houseknecht 2000). Body fat also has a number of other roles including; insulation, protection, heat production and immunity (Christie 1978; Norgan 1997; Trayhurn et al. 1999; Trayhurn et al. 2001). In sheep, body fat is located in the abdominal cavity (visceral), under the skin (subcutaneous) and within the muscle (intramuscular) (Louveau et al. 2016). These regions of body fat tissue vary in size and proportion depending on animal age and breed (Russel 1984a).

Subcutaneous fat is found underneath the skin (Louveau et al. 2016). This is the fat that is predominately measured by BCS, therefore, it will be described in more detail than the other body fat locations. Subcutaneous fat makes up around 25% of the total body fat in Merinos (Thompson et al. 1987) and slightly more in crossbred sheep (Lambe et al. 2003). It was theorised that subcutaneous fat tissue evolved as an adaptation to thermal insulation. However, this has been disproven due to the fact that both tropical and subarctic mammals produce subcutaneous fat, regardless of the need for thermal insulation (Pond 1992). Subcutaneous fat tissue is deposited if there is excess energy, once maintenance requirements have been met (Forbes 2000).

In periods when there is excess feed, animals can store this additional energy as body fat (Bauman and Currie 1980; Bauman 2000; Yilmaz et al. 2011). During periods of feed deficit, the animal may need to mobilise stored energy to meet maintenance, pregnancy and lactation requirements (Bauman and Currie 1980; Bauman 2000; Yilmaz et al. 2011). In some instances, the mobilisation of body fat is greater than the deposition, therefore, the animal is in a state of negative energy balance and catabolism of other tissues occurs (Sorensen et al. 2002).

The energy requirements of the ewe increase greatly in late-pregnancy and lactation (Russel et al. 1967; Rattray et al. 1974; Bauman and Currie 1980; Rattray 1986; Nicol and Brookes 2007). When the ewe is lactating and rearing two or more lambs (Sorensen et al. 2002), she is in a period of high energy demand (Chilliard et al. 2000), which can cause a period of negative energy balance. During this period of negative energy balance the ewe uses body fat to meet the energy requirements of milk production (Banchero et al. 2004; Cannas 2004). The relationship between BCS and milk production will be discussed in Section 2.6. The level of body condition loss is directly related to milk yield (Borg et al. 2009). Borg et al. (2009) suggested that ewes with higher genetic merit for lamb growth and milk production tended to lose more body condition during lactation, but compensated by increasing BCS during breeding and gestation. However, this constant loss and gain in BCS can be attributed to potentially higher feed costs. This is due to the energy required to increase in 1 kg of live weight being approximately 55 MJ ME/kg, while only 30 MJ ME/kg is provided when live weight is lost (Nicol and Brookes 2007). As a result, there is a net loss of 25 MJME/kg for each cycle of losing and then regaining live weight (Nicol and Brookes 2007). The net result is that gain and loss of BCS requires more feed in order to reach the same BCS as an animal that maintains the same BCS throughout the year (Morel et al. 2016).

2.5.1 Physiological factors influencing body fat metabolism

The physiological factors influencing body fat metabolism include growth hormone, insulin and leptin (Bauman 2000; Houseknecht et al. 2000; Verbeek et al. 2012). Growth hormone is produced in the pituitary gland and plays an important role in partitioning nutrients between various functions, including fat storage (Bauman 2000). Growth hormone supplementation can result in decreased fat storage in growing animals and increased rates of nitrogen retention (Pell et al. 1990; Etherton and Bauman 1998). This decrease in fat storage was due to a decrease in the amount of glucose being turned into fat and an increase in the amount being utilised for either meat or milk production (Spencer et al. 1985; Deligeorgis et al. 1988).

Insulin is an important regulator of fat formation (Vernon 1992; Travers et al. 1997; Yokus et al. 2006) and inhibits the fat metabolism actions of growth hormone (Rhoads et al. 2004). During the first two months of pregnancy, fatty acid metabolism in omental body fat favours fat formation (Guesnet et al. 1991; Yokus et al. 2006). In late pregnancy this switches to fat mobilisation (Guesnet et al. 1991; Barber et al. 1997; Nazifi et al. 2002) as body fat has diminished responsiveness to insulin and insulin activity falls (Knopp et al. 1973; Nazifi et al. 2002; Yokus et al. 2006). Insulin levels continue to be lower during lactation compared with non-lactating sheep (Sorensen et al. 2002).

Insulin has been shown to upregulate leptin expression in rodents, humans, cows and sheep (Houseknecht et al. 2000; Sorensen et al. 2002; Tokuda et al. 2002). Leptin is secreted by fat tissue and regulates energy balance (Verbeek et al. 2012). It acts on receptors in the hypothalamus to regulate feed intake and energy expenditure to help achieve energy balance (Zhang et al. 1994; Barash et al. 1996; Hoggard et al. 1998; Morrison et al. 1998; Vernon and Houseknecht 2000; Verbeek et al. 2012). Leptin has been well documented in human and rodent species but less so in ruminants (Chilliard et al. 2005). Morrison et al. (1998) reported that administration of leptin to sheep resulted in a reduction in food intake. However, Sorensen et al. (2002) reported that although the lactating ewe was in a negative energy balance (low leptin levels) she also had a reduced appetite when fed *ad libitum*, indicating there are other factors influencing energy balance in sheep. Therefore, leptin levels increase when the animal is close to energy balance, except during lactation where there are factors at play, other than gut fill, that need further investigation in sheep.

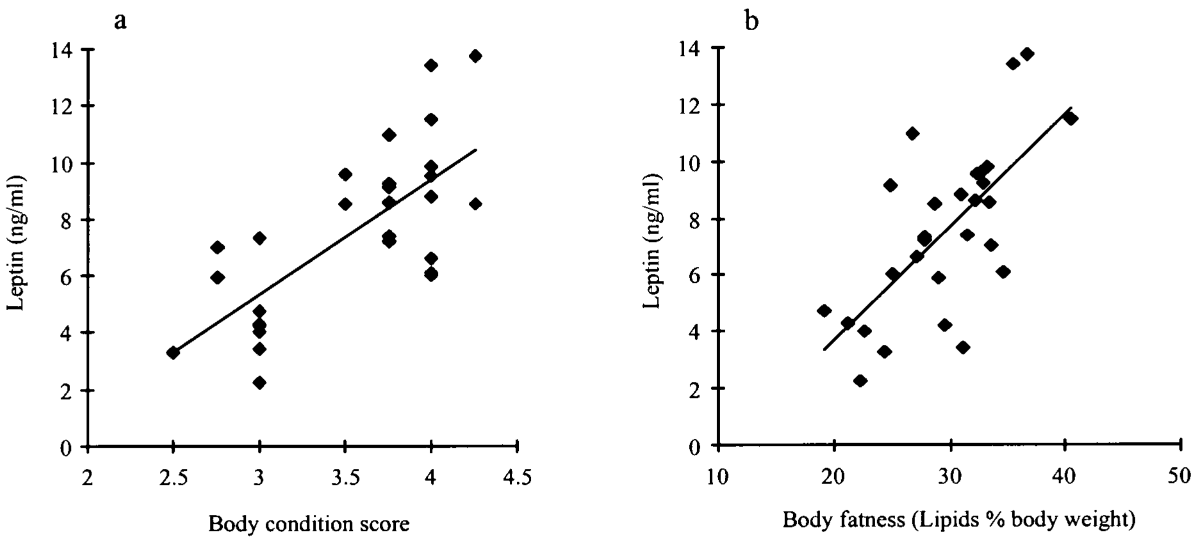


Figure 2.2. (a) Relationship between Leptin (ng/ml) and body condition score (0-5) in sheep. (b) Relationship between Leptin and body fatness (Lipids as a percentage of body weight) in sheep (reproduced from Delavaud et al. 2000).

Fat tissue is the main source of leptin and therefore, there is a positive relationship (r=0.68) between leptin and body fat (Figure 2.2, Considine et al. 1996; Ostlund Jr et al. 1996; Delavaud et al. 2000; Geary et al. 2003; Kaminski et al. 2015). This positive relationship is similar to that of BCS and leptin (r=0.72, Delavaud et al. 2000). Kaminski et al. (2015) reported that overfed non-pregnant ewes had greater leptin levels than non-pregnant underfed and non-pregnant control ewes. Therefore, the greater the fat or BCS, the greater the leptin levels.

2.6 Association of body condition score and reproductive and productive performance in ewes

The relationship between individual BCS, reproduction traits and production traits have been examined by numerous studies across different breeds and environments. In addition, the relationships have been recently reviewed (Kenyon et al. 2014), therefore, the following sections only summarise those findings with the addition of more recent studies.

2.6.1 Ewe reproductive performance

A summary of studies on the relationship between BCS and length of breeding season, ovulation rate and conception rate is shown in Table 2.4. BCS has a positive relationship with the length of the breeding season although the effect is small. Therefore, it is unlikely that BCS could be utilized to shift the breeding season (Kenyon et al. 2014). Ovulation rate determines the number of lambs born (NLB) and therefore sets the potential for the number of lambs weaned (NLW). Ovulation rate and conception rate both have a positive relationship with BCS up to a BCS of 3.0 after which there were no further increases (Table 2.4). Therefore, farmers should aim for an individual ewe BCS of 3.0 at breeding in order to positively influence the ovulation and conception rate.

In studies where ovulation rate has been measured, the percentage of corpora lutea without viable embryos (also termed ova loss) has been used as a measure for embryo loss (Gunn et al. 1972; Gunn and Doney 1975; Gunn and Doney 1979; Rhind et al. 1984a; Rhind et al. 1984b). Therefore, both ova loss and embryo loss in the following studies are referred to as embryo mortality. There are mixed results in studies in regards to the effect of BCS on embryo mortality. Embryo mortality and

BCS have been reported to have no relationship (Cumming et al. 1975; Rhind et al. 1984a), a negative relationship (Gunn et al. 1972; Gunn and Doney 1975), a positive relationship (Rhind et al. 1984b) or ewes with either low or high BCS have been found to display greater embryo mortality than ewes of moderate BCS (Abdel-Mageed 2009). While these results are not clear, it appears that both low and high BCS should be avoided to attempt in limit embryo mortality.

Many studies have examined the relationships between BCS and either barrenness, fertility, pregnancy rate or lambing rate. For the purpose of this section, these terms have been combined into either 'pregnant' or 'non-pregnant'. Pregnancy rate has been reported to have either a positive relationship with BCS (Gunn and Doney 1979; Gonzalez et al. 1997; Atti et al. 2001; Kenyon et al. 2004b; Kleemann and Walker 2005; Esmailizadeh et al. 2009; Yilmaz et al. 2011; Griffiths et al. 2016; Griffiths et al. 2018), no relationship above a BCS of 2.5 (Kenyon et al. 2004b; Yilmaz et al. 2011) or above a BCS of 3.5 (Maurya et al. 2009) and a negative relationship with a BCS of 4.0 (Sejian et al. 2009). These studies suggest that both a low and a high BCS result in lower pregnancy rates. Therefore, farmers should aim for a BCS between 2.5 to 3.5 at breeding to optimise pregnancy rates as there appears to be little advantage in exceeding a BCS of 3.5.

Table 2.4. Summary of studies on the relationship between ewe body condition score (BCS) and length of mating, ovulation rate and conception rate (adapted from Kenyon et al. 2014)

Reference	BCS measure and range	Nutritional treatments	BCS and breeding season	BCS and ovulation rate	BCS and conception rate
Gunn et al. (1969)	Breeding, 1.5-3.0	Low, maintenance, high		+	
Bastiman (1972)	Breeding, 2.5-3.5	N/S		+	+
Gunn et al. (1972)	Breeding, 1.5-3.0	Fed to maintain BCS		+	
Gunn and Doney (1975)	Breeding, 1.0-3.0	Low, maintenance, high		+	
Gunn and Doney (1979)	Breeding, 2.0-3.0	Fed to maintain BCS		+	
Newton et al. (1980)	Breeding, 2.0-4.0	Fed to maintain BCS	+ late in breeding season	+	
Knight and Hockey (1982)	Pre-breeding	Commercial		+	
(Rhind et al. 1984a)	Breeding, 1.8-2.8	Fed to maintain BCS		+	
Rhind et al. (1984b)	Pre-breeding, 2.5-3.0 and 3.25-3.75	Fed to maintain BCS		+	
Rhind and McNeilly (1986)	Pre-breeding, 1.8 and 2.9	Fed to maintain BCS		+	
(McNeilly et al. 1987)	Pre-breeding, 1.8-2.9	Fed to maintain BCS		+	
Gunn et al. (1988)	Breeding, ≤1.5, 1.75-2.0, 2.25-2.5 and ≥2.75	Low, high		+ and + to 2.25-2.5 in two differing breeds	
Gunn et al. (1991a)	Pre-breeding, ≤2.25, 2.5 and ≥2.75	Low, high		+ and + to 2.5 in two differing breeds	+ and + to BCS 2.5 in two differing breeds
Gunn et al. (1991b)	Pre-breeding, ≤2.25, 2.5-2.75 and ≥3.0	Low, maintenance		+ to BCS 2.5-2.75	+ to 2.5-2.75 then –
Forcada et al. (1992)	Breeding, ≤2.5 and ≥2.75	Fed to maintain BCS	+	+	
Rondon et al. (1996)	Breeding, ≤2.5 and ≥2.75	High	+		
Viñoles et al. (2002)	Breeding, 1.9 and 4.1	Fed to maintain BCS		+	
Kleemann and Walker (2005)	Breeding,	Commercial		+	

	Pre-breeding, 2.5, 3.0-3.5 and 4.0	Fed to maintain BCS	+ to BCS 3.0-3.5 then –
Vatankhah et al. (2012)	Pre-breeding, 1.0-4.0	Commercial conditions	+
(Corner-Thomas et al. 2015c)	Breeding BCS	Commercial conditions	

+ positive relationship between BCS and trait
– negative relationship between BCS and trait

2.6.2 *Ewe fecundity, number of lambs born and lamb survival*

The relationship between BCS at breeding and fecundity (measured as number of foetuses per ewe), number of lambs born (NLB) and lamb survival are presented in Table 2.5. Fecundity has shown to have a positive relationship with BCS in a number of studies (Gunn et al. 1988; Gunn et al. 1991a; Kenyon et al. 2004b; Kleemann and Walker 2005; Sezenler et al. 2011b; Corner-Thomas et al. 2015c), with one reporting a negative relationship with BCS (Rhind et al. 1984b). The negative relationship between BCS and fecundity reported by Rhind et al. (1984b) may have been due to the mean BCS at mating of 2.74 and 3.35 between the two groups and the small number of animals (n=19 vs 20). Therefore, the literature would indicate that there is a positive relationship between BCS and fecundity and farmers should aim for a greater BCS up to a BCS between 3.0 and 3.5 at breeding.

Table 2.5. Summary of studies examining the relationship between ewe body condition score (BCS) and the number of foetuses per ewe, number of lambs born (NLB) and lamb survival (adapted from Kenyon et al. 2014).

Reference	BCS measure and range	Nutritional treatments	BCS and number of foetuses per ewe relationship	BCS and NLB relationship	BCS and lamb survival relationship
Gunn et al. (1969)	Breeding, 1.5-3.0	Low, maintenance, high		+	
Pollott and Kilkenny (1976)	Breeding, BCS range not stated	N/S		+	
Adalsteinsson (1979)	Pre-breeding, 2.0-4.0	Commercial conditions		+ to BCS 3.0-3.5	
Newton et al. (1980)	Breeding, 2.0-4.0	Fed to maintain BCS		+	
Gunn et al. (1983)	Pre-breeding, ≤2.25, 2.5-2.75, ≥3.0	Low, high		2.5-2.75 greater than BCS ≤2.25, ≥3.0	
Rhind et al. (1984b)	Pre-breeding, 2.5-3.0 and 3.25-3.75	Fed to maintain BCS	-	NR	
Gunn et al. (1988)	Breeding, ≤1.5, 1.75-2.0, 2.25-2.5 and ≥2.75	Low, high	+ in one breed, NR in other breed		
Gunn et al. (1991a)	Pre-breeding, ≤2.25, 2.5 and ≥2.75	Low, high	High BCS + to 2.5		
Gunn et al. (1991b)	Pre-breeding, ≤2.25, 2.5-2.75 and ≥3.0	Maintenance, high		BCS 2.5-2.75 greater than ≤2.25, ≥3.0	
Al-Sabbagh et al. (1995)	Pre-lambing, BCS 2.5, 3.0, 3.5	High			NR
Gonzalez et al. (1997)	Breeding, 2.0, 2.5, 3.0, 3.5, 4.0	Commercial conditions		+	
Litherland et al. (1999)	Pre-lambing, 1.5, 2.5	Low, high			+ in one of two studies
Atti et al. (2001)	Pre-breeding, range not stated	Commerial conditions		+ to BCS 3.5-4.0	
Kenyon et al. (2004b)	Breeding, 1.5 to 4.0	Commercial conditions	+ to BCS 2.0 in one breed and + to BCS 3.0 in second breed		
Oregui et al. (2004)	Breeding, ≤1.75. 2.0-2.25, 2.5-2.75, 3.0-3.25 and ≥3.5	Commercial conditions		+ to BCS 2.5-2.75	
Kleemann and Walker (2005)	Breeding, BCS range not stated	Commercial conditions	+	+	+
Rozeboom et al. (2007)	Pre-lambing, 1.5 to 3.5	N/S		NR	
Everett-Hincks and Dodds (2008)	Mid-preg, range not stated	Commercial conditions			+
Abdel-Mageed (2009)	Pre-breeding	Maintenance		+ to BCS 2.5 then – after for BCS 4.0	

Kenyon et al. (2011)	Mid-preg, ≤2.0, 2.5, ≥3.0	Med, high			BCS 2.5 lower than ≤2.0
Oldham et al. (2011)	Day 100 pregnancy, 2.0, 3.0	Various feeding			NR
(Sezenler et al. 2011b)	Breeding 2, 3, 4 and 5	Fed to maintain BCS	+	NR	
(Aliyari et al. 2012)	Pre-breeding, 2.0, 2.5, 3.0 and 3.5+	Ad libitum		NR	
Kenyon et al. (2012a)	Mid-preg, 2.0, 2.5, 3.0	Med, high			BCS 2.5 lower than 2.0
Kenyon et al. (2012b)	Mid-preg, 2.0, 2.5, 3.0	Med, high			NR
Vatankhah et al. (2012)	Pre-breeding, 1.0-4.0	Commercial conditions		+	
(Corner-Thomas et al. 2015a)	Late preg, lactation	Low, med, high			BCS 2.0 and 2.5 greater than 3.0
(Corner-Thomas et al. 2015c)	Breeding BCS	Commercial conditions	+ up to a BCS of 3		

+ positive relationship between BCS and trait
– negative relationship between BCS and trait
NR no relationship

The NLB and BCS has been found to either have a positive relationship (Gunn et al. 1969; Newton et al. 1980; Gonzalez et al. 1997; Kleemann and Walker 2005), positive relationship up to a BCS of 3.0 and 3.5, or no relationship with BCS at mating (Rhind et al. 1984b; Rozeboom et al. 2007; Sezenler et al. 2011b). Combined these results indicate that to maximise number of foetuses per ewe and NLB, farmers should aim for a BCS between 3.0 and 3.5 at breeding as there appears to be little advantage in exceeding a BCS of 3.5 for NLB.

Lamb survival has had either a positive relationship with BCS (Litherland et al. 1999; Kleemann and Walker 2005; Everett-Hincks and Dodds 2008), a negative relationship (Kenyon et al. 2011; Kenyon et al. 2012a; Corner-Thomas et al. 2015a) or no relationship (Al-Sabbagh 2009; Oldham et al. 2011; Kenyon et al. 2012b). The study by Al-Sabbagh (2009) had a small number of animals (n=90) which likely limited its ability to detect a difference in survival. Also of note, is that in the studies that reported a negative relationship were for ewes fed *ad libitum* (Kenyon et al. 2011; Kenyon et al. 2012a; Corner-Thomas et al. 2015a). Collectively, these results indicate that there can be a positive relationship between BCS and lamb survival, however, this is very study specific as there are likely numerous farm specific environmental factors influencing lamb survival (Kenyon et al. 2019). Therefore, more research is required to understand the effects of greater BCS on lamb survival in different farming systems.

2.6.3 Birth weight, number of lambs weaned, lamb growth and lamb weaning weight

The effect of BCS on birth weight, lamb growth and weaning weight (WWT) are summarised in Table 2.6. Lamb birth weight showed no relationship with BCS at breeding (Gibb and Treacher 1980; Gibb and Treacher 1982; Hossamo et al. 1986; Al-Sabbagh et al. 1995; Aliyari et al. 2012), at mid-pregnancy (Kenyon et al. 2011; Kenyon et al. 2012a; Kenyon et al. 2012b) or at lambing (Karakuş and Atmaca 2016). Although, lamb birth weight did show a positive relationship with BCS at breeding (Maurya et al. 2009; Sejian et al. 2009), at mid-pregnancy (Everett-Hincks and Dodds 2008; Oldham et al. 2011) or at pre-lambing (Hossamo et al. 1986; Molina et al. 1991) and a positive relationship up to a BCS of 2.5 in late-pregnancy (Corner-Thomas et al. 2015a) or up to a BCS of 3.5 at breeding (Vatankhah et al. 2012). It is apparent there is a large variation in results between the studies. This could be due to timing in BCS measurement, number of foetuses per ewe and nutrition of the ewe prior to, at and after the BCS measurement. The feed demand of ewes significantly increases in late-pregnancy (Rattray 1986; Nicol and Brookes 2007), which occurs when the ewe cannot meet the increased feed requirements, resulting in the utilisation of body fat (see Section 2.5). Therefore, it could be hypothesised that, the effect of BCS during late pregnancy may influence birth weight more than BCS at breeding or pregnancy scanning. However as outlined above, there are mixed results for BCS measured at the same time perhaps indicating that there is an optimum birth weight for various litter sizes (Kenyon et al. 2019).

Lamb growth has either a positive relationship with BCS at mid-pregnancy (Gibb and Treacher 1980; Wilson et al. 1985; Atti et al. 1995; Kenyon et al. 2004a; Alvarez et al. 2007) or no relationship with BCS at breeding (Hossamo et al. 1986) or mid-pregnancy (Gibb and Treacher 1982). The studies that reported no relationship between BCS and lamb growth were conducted with ewes fed at high levels during pregnancy and lactation, most likely providing the ewes with enough energy for adequate milk production and therefore, lamb growth throughout lactation, regardless of BCS. These results suggest there is a general positive relationship between BCS and lamb growth to weaning. Therefore, farmers should aim for a greater BCS at pre-breeding and ewes should be fed at high levels throughout late-pregnancy and lactation to ensure adequate BCS and to increase lamb growth rates.

As there is a general positive relationship between BCS and lamb growth it would be expected that there would be a positive relationship between BCS and milk production. However, the reports relating to milk production and BCS have been somewhat inconsistent depending on timing of measurement. Milk production showed no relationship with BCS when measured at breeding and/or in mid-pregnancy in Scottish halfbred ewes (Gibb and Treacher 1982; Hossamo et al. 1986) or a positive relationship with BCS measured in late pregnancy in Awassi (Hossamo et al. 1986) and Scottish halfbred ewes (Gibb and Treacher 1980). These results suggest that BCS prior to lambing has a positive relationship with milk production, however, BCS at breeding has no effect due to a number of factors affecting whether or not that BCS is still present at lambing. Therefore, farmers should aim for a greater BCS at or prior to lambing to increase the milk production of the ewe.

Table 2.6. Summary of studies examining the relationship between ewe body condition score (BCS) and lamb birth weight, lamb growth and lamb weaning weight (WWT, adapted from Kenyon et al. 2014).

Reference	BCS measure and range	Nutritional treatments	BCS and birth weight relationship	BCS and lamb growth relationship	BCS and WWT relationship
Gibb and Treacher (1980)	Pre-lambing, 2.4 and 3.2	Low, High	NR	+	
(Gibb and Treacher 1982)	Day 90 pregnancy, 2.6 and 3.3	Low, High in pregnancy, high in lactation	NR	NR	
Wilson et al. (1985)	Pre-lambing, 1.0 to 3.5	N/S		+ to BCS 1.5	
Hossamo et al. (1986)	Pre-breeding and pre-lambing, 1.0 to 3.5	Commercial	NR/+	NR	NR
Molina et al. (1991)	Pre-lambing, <2.5, 2.5 to 3.0, >3.0		+		+ to BCS >3.0
Al-Sabbagh et al. (1995)	Pre-lambing BCS 2.5, 3.0, 3.5	High	NR		NR
Atti et al. (1995)	Pre-lambing <2 and >3	Maintenance		+	
Litherland et al. (1999)	Pre-lambing, 1.5 and 2.5	Low, high		NR	NR
Kenyon et al. (2004a)	Breeding, 1.5 to 4.0		BCS 3.5-4.0 <3.0	+	
Alvarez et al. (2007)	Pre-breeding	Commercial conditions		+ for twins, + and NR for singletons	
Everett-Hincks and Dodds (2008)	Mid-pregnancy, BCS range not stated	Commercial conditions	+		
Maurya et al. (2009)	Breeding 2.5, 3.0, 3.5	Commercial conditions	+		
Sejian et al. (2009)	Pre-breeding, 2.5, 3.0-3.5 and 4.0	Fed to maintain BCS	+		+ to BCS 3.0-3.5
Kenyon et al. (2011)	Mid-preg, ≤2.0, 2.5, ≥3.0	Med, high	NR		BCS ≤2.0 lower than 2.5
Mathias-Davis et al. (2011)	Scanning, pre-lambing & weaning	Commercial			+
Oldham et al. (2011)	Day 100 of pregnancy, 2.0 and 3.0	Various feeding levels	+ in two of four studies		
Saul et al. (2011)	Mid-preg, lambing	Commercial conditions			+
(Aliyari et al. 2012)	Pre-breeding, 2.0, 2.5, 3.0 and 3.5+	Ad libitum	NR		NR
Kenyon et al. (2012a)	Mid-preg, 2.0, 2.5, 3.0	Med, high	NR		+ to BCS 2.5

Kenyon et al. (2012b)	Mid-preg, 2.0, 2.5, 3.0	Med, high	NR	+ to BCS 2.5
Vatankhah et al. (2012)	Breeding 1.0-4.0	Commercial conditions	+ to BCS 3.5	+ to BCS 3.5
(Corner-Thomas et al. 2015a)	Late preg, lactation	Low, med, high	+ BCS 2.5	+
Karakuş and Atmaca (2016)	Lambing 2.5,3.0,3.5	Commercial conditions	NR	NR

+ positive relationship between BCS and trait
– negative relationship between BCS and trait
NR no relationship

Total lamb weaned (TLW) is a combination of number of lambs weaned (NLW) and their weaning weight (WWT) per ewe lambed (Mathias-Davis et al. 2011). TLW is an important composite trait, as farm income is driven by TLW (Morel and Kenyon 2006; Hawkins and Wu 2011; Kenyon et al. 2019). The NLW and BCS showed a positive relationship up to BCS 3.0 (Kleemann et al. 2006; Saul et al. 2011; Vatankhah et al. 2012), while, lamb WWT has either had no relationship with BCS (Aliyari et al. 2012; Karakuş and Atmaca 2016) or a positive relationship up to a BCS of 3.5 (Saul et al. 2011). BCS at mating and BCS at lambing had no effect on TLW among the same litter sizes (Mathias-Davis et al. 2011). Similarly, lambing BCS in Romney ewes ranging between 2.0 to 3.0 had no effect on TLW (Kenyon et al. 2012a). The reason for a lack of effect of BCS on TLW could be due to the small BCS range of 2.0 to 3.0. Further, when comparing the same litter sizes, TLW are likely to be similar due to the strong influence on NLW. The reason for potential inconsistency among these results could be the timing of the measurements and the different BCS ranges observed in each study. Although it is unclear what effect BCS has on TLW, farmers should aim for a BCS between 3.0 and 3.5 to optimise NLW and lamb WWT.

2.7 Options to achieve optimal body condition score in a flock

2.7.1 Nutrition

Body condition score is an optimum trait, similar to birthweight, with extreme values being considered undesirable (Kenyon et al. 2014). Low BCS has negative impacts on reproductive performance and lamb growth, and high BCS having either no additional effect or negative consequences (see Section 2.6). Sheep performance generally plateaus at a BCS range of 3.0 to 3.5 (Atti et al. 2001; Yilmaz et al. 2011; Kenyon et al. 2012a; Vatankhah et al. 2012; Kenyon et al. 2014). Therefore, ewes of very high BCS are inefficient as maintenance feeding requirements are higher, for no additional increase in production. Morel et al. (2016) reported that an increase in BCS from 2.0 to 3.0 required 220 MJME, whereas an increase from a BCS of 3.0 to 4.0 required 593 MJME. Given the lack of additional production for most traits above a BCS of 3.0, there is likely no benefit for the additional feed required to increase BCS above 3.0. Therefore, it could be suggested that from a nutritional perspective, maintaining all ewes at a BCS of 3.0 or slightly above this at 3.5 within a flock and allowing for up to a BCS loss of 1.0 during pregnancy and lactation to allow for more flexible farm management (Kenyon et al. 2004b; Morel et al. 2016; Kenyon and Cranston 2017).

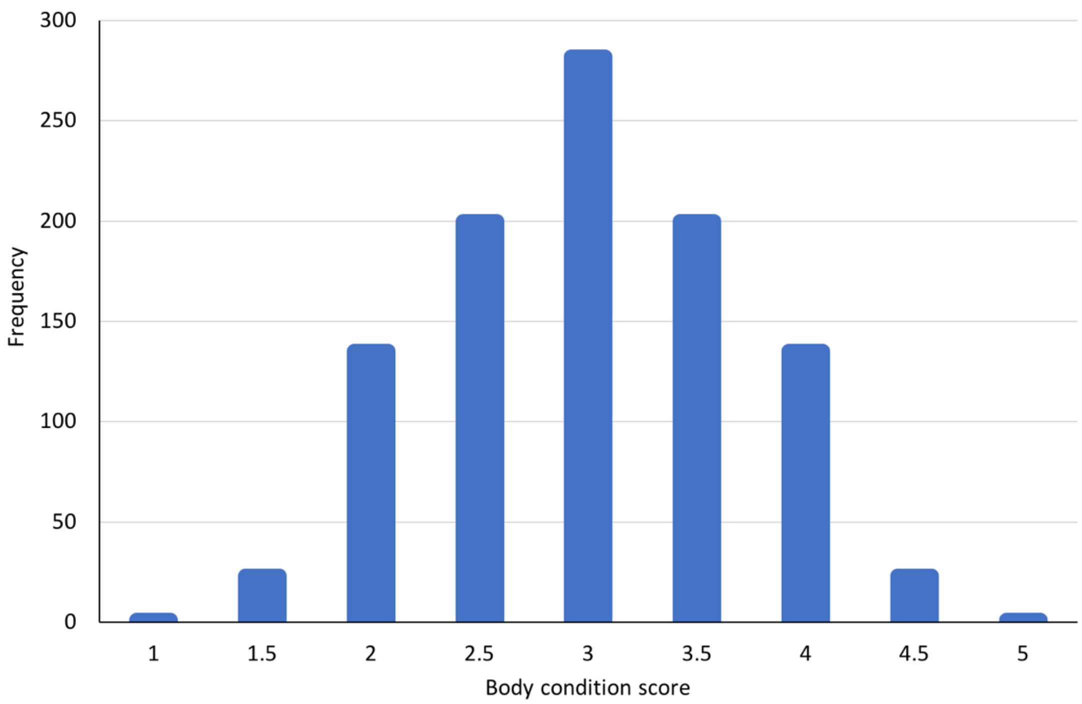


Figure 2.3. Frequency of body condition score (BCS) in a typical commercial sheep flock based on a phenotypic standard deviation of 0.6 (Shackell et al. 2011).

Within a flock with no selection pressure BCS is likely to be normally distributed, with a range of 1.0 to 5.0 (Robinson et al. 2002; Kenyon et al. 2004a). Therefore, in a hypothetical flock of 1000 ewes, the BCS spread would be similar to that shown in Figure 2.3, with a mean of 3.0 and using a standard deviation of 0.60, as reported by Shackell et al. (2011). In this scenario most ewes will have a BCS in the range of 2.0 to 4.0 as reported by Russel (1984a).

Hypothetical options available to farmers to achieve the aim of having no ewes below a BCS of 3.0 and as few as possible above BCS 3.5 are given in the following sections based on scenarios using the base flock from Figure 2.3. The energy required for a gain in BCS is based on Morel et al. (2016). In that study they quantified the energy requirements for 0.5 unit increases in BCS over the range of 1.5 to 4.5.

2.7.1.1 *Scenario one: Entire flock fed as one mob to increase the condition of BCS 2.0 ewes to BCS 3.0*

In this scenario, the vast majority of the flock's ewes with a BCS of below 3.0 are in the BCS 2 category (i.e. 135 and 200 for BCS 2.0 and 2.5 respectively, Figure 2.3). Therefore, if these ewes could gain one unit of BCS the number of ewes within the flock below 3.0 would decrease from 359 to 0 (Table 2.7). The following assumptions were made:

i. all ewes regardless of BCS consumed the same amount of feed above their maintenance requirements.
ii. the energy required to increase one unit in BCS from 2.0 to 3.0 is 220 MJME/ewe (Morel et al. 2016).
iii. no time-frame was put upon ewes to gain this BCS.
iv. the energy required to move from BCS 1.0 to 1.5 (4.5 MJME/ewe) is assumed to be half of that required to move from 1.5 to 2.0 (9 MJME/ewe). This assumption has been made due to Morel et al. (2016) only measuring the extra energy to gain BCS above BCS 1.5 to 4.5.
v. the energy required to move from BCS 4.5 to 5.0 is assumed to be 510 MJME/ewe (obtained from the linear relationship with the other 0.5 increase increments of: $y = 161.89x - 299.75$, Morel et al. 2016)
vi. the final BCS achieved has been rounded to the nearest 0.5 score.

This approach would increase the BCS of all ewes (Table 2.7) and the mean would also increase from 3.0 to 3.7. Ewes of BCS lower than 2.0 require less energy to increase BCS than ewes at or above a BCS of 2.5. Therefore, ewes of an original BCS of 1.0, 1.5 and 2.0 will gain 2.0, 1.5 and 1.0 units of BCS respectively and thus all ewes have a final BCS of 3.0. In contrast, ewes of BCS greater than 3.0 at the start of this scenario had greater energy requirements to gain a unit of BCS, so their gain in BCS was less (i.e. 0.5, 0 and 0 unit gain in BCS for ewes with an original BCS of 3.5, 4.0 and 4.5 respectively).

Table 2.7. The estimated feed required to increase the average body condition score (BCS) across the flock in the hypothetical scenario of 1000 ewes fed at levels to increase BCS 2.0 ewe to a BCS of 3.0.

Original BCS	n[1]	BCS change estimated[2]	BCS change rounded[3]	Final BCS	Total energy required for change (MJME)
1.0	1	1.88	2.0	3.0	220
1.5	23	1.44	1.5	3.0	5,060
2.0	135	1.00	1.0	3.0	29,700
2.5	200	0.56	0.5	3.0	44,000
3.0	282	0.45	0.5	3.5	62,040
3.5	200	0.31	0.5	4.0	44,000
4.0	135	0.23	0	4.0	29,700
4.5	23	0.18	0	4.5	5,060
5.0	1	0	0	5.0	220
Average		0.67	0.67	3.67	
TOTALS	1,000				220,000

[1] Numbers are calculated from a hypothetical flock of 1000 ewes with a standard deviation of 0.6 taken from the population used in Shackell et al. (2011).

[2]BCS change estimated from increased feeding resulting in an extra 220 MJME/ewe consumed Morel et al. (2016).

[3]The change is rounded to the nearest 0.5 as this is the lowest increment BCS is measured in.

From Table 2.7 it can be seen that the estimated total energy required to increase BCS 2.0 ewes to BCS 3.0 with the remainder of the flock fed at the same level of 220 MJME/ewe is 220,000 MJME. There would be zero ewes under a BCS of 3.0 in scenario one, with the BCS change being rounded, however, there would be more ewes above an ideal BCS target of 3.0 (i.e. 359 and 641 for the original and revised scenarios, respectively). These higher BCS ewes will be less efficient, therefore, this is far from the optimal scenario.

2.7.1.2 Scenario two: Flock fed as two mobs, one to increase the condition of BCS 2.0 ewes to BCS 3.0 and the other to maintain body condition of the remaining ewes.

In this scenario, the flock is separated into two mobs. Ewes of less than BCS 3.0 in one mob and ewes that are of BCS 3.0 or above in the other mob. The same assumptions as scenario one are applied to scenario two. Similar to scenario one, ewes under a BCS of 3.0 were fed to increase a unit BCS for a ewe of BCS 2.0 (Table 2.8) and the ewes at or above a BCS of 3.0 were fed maintenance requirements. At the end of the scenario the numbers of ewes within the flock below BCS 3.0 would decrease from 359 to 0. This scenario has been termed a 'minimum' BCS approach by Kenyon et al. (2004a), as opposed to the 'average' BCS approach i.e. scenario one.

Table 2.8. The estimated feed required to increase the feeding levels to increase body condition score (BCS) for ewes below a BCS of 3.0 in a hypothetical flock of 1000 ewes.

Original BCS	n[1]	BCS change estimated[2]	BCS change rounded[3]	Final BCS	Total energy required for change (MJME)
1.0	1	1.88	2.0	3.0	220
1.5	23	1.44	1.5	3.0	5060
2.0	135	1.00	1.0	3.0	29700
2.5	200	0.56	0.5	3.0	44000
3.0	282	0.00	0.0	3.0	0
3.5	200	0.00	0.0	3.5	0
4.0	135	0.00	0.0	4.0	0
4.5	23	0.00	0.0	4.5	0
5.0	1	0.00	0.0	5.0	0
Average		0.54	0.56	3.56	
TOTALS	1000				78,980

[1] Numbers are calculated from a hypothetical flock of 1000 ewes with a standard deviation of 0.6 taken from the population used in Shackell et al. (2011).
[2]BCS change estimated from increased feeding resulting in an extra 220 MJME/ewe consumed Morel et al. (2016).
[3]The change is rounded to the nearest 0.5 as this is the lowest increment BCS is measured in.

From Table 2.8 it can be seen that the estimated total energy required to increase BCS 2.0 ewes to BCS 3.0 with 220 MJME/ewe and the remainder of the flock fed at maintenance requirements are 78,980 MJME. The number of ewes under a BCS of 3.0 (zero) and over BCS 3.0 would be similar to scenario one (359 and 641 for the original and revised scenarios, respectively), however, the total feed requirements is much lower than scenario one (i.e. 78,980 vs 220,000). This scenario still has ewes above BCS 3.0 which is less efficient.

2.7.1.3 Scenario three: Flock fed as three mobs, one to increase condition (i.e. original BCS 2.0 to 3.0 ewes, one to maintain (3.0 to 3.0 ewes) and one to decrease condition (i.e. BCS 4.0 to 3.5).

The farmer could separate out the flock into three mobs. The ewes below a BCS of 3.0 would be fed to increase BCS (mob 1), those ewes with BCS between 3.0 and 3.5 would be fed at maintenance levels (mob 2) and ewes above a BCS of 3.5 would have restricted feed intakes to decrease BCS (mob 3). This type of approach has been termed targeted feeding (Beef+Lamb New Zealand 2019b). The following assumptions have been made in this scenario:

i. mob 1 ewes (BCS of 1.0, 1.5, 2.0 and 2.5) fed 220 MJME/ewe (Morel et al. 2016).
ii. mob 2 (BCS of 3.0 and 3.5) ewes fed maintenance levels.
iii. mob 3 (BCS of 4.0, 4.5 and 5.0) are restricted to aim for a unit decrease in BCS from 4.5 to 3.5 (7.0 kg).
iv. there is no time-frame put upon the ewes to gain or lose condition.
v. the energy required to move from BCS 1.0 to 1.5 (4.5 MJME/ewe) is assumed to be half of that required to move from 1.5 to 2.0. This assumption has been made due to Morel et al. (2016) only measuring the energy increases from 1.5 to 4.5.
vi. the energy provided by 1 kg decrease in live weight is 20 MJME (Nicol and Brookes 2007) and 1 unit BCS is equivalent to 7.0 kg live weight (Table 2.3).
vii. the final BCS achieved has been rounded to the nearest 0.5 score.

The three mobs would change BCS as outlined in **Table 2.9**. Mob 1 would increase BCS while mob 2 would maintain and mob 3 would slightly decrease BCS. From these changes the flock mean BCS would increase from 3.0 to 3.22.

Table 2.9. The estimated feed required to increase the feeding levels for ewes below a body condition score (BCS) of 3.0, maintain the ewes between BCS of 3.0 and 3.5 and restrict the ewes above a BCS of 2.5 in a hypothetical flock of 1000 ewes.

Original BCS	n[1]	BCS change estimated[2]	BCS change rounded[3]	Final BCS	Total energy required for change (MJME)
1.0	1	1.88	2	3.0	18
1.5	23	1.44	1.5	3.0	5,267
2.0	135	1.00	1	3.0	29,700
2.5	200	0.56	0.5	3.0	29,800
3.0	282	0	0	3.0	0
3.5	200	0	0	3.5	0
4.0	135	-1	-1.0	3.0	-18,900
4.5	23	-1	-1.0	3.5	-3,220
5.0	1	-1	-1.0	4.0	-140
Average		0.21	0.22	3.22	
TOTALS	**1000**				**56,720**

[1] Numbers are calculated from a hypothetical flock of 1000 ewes with a standard deviation of 0.6 taken from the population used in Shackell et al. (2011).
[2]Energy required for change retrieved from Morel et al. (2016).
[3]The change is rounded to the nearest 0.5 as this is the lowest increment BCS is measured in.

The option to feed the three different BCS groups accordingly results in the lowest total feed requirements (56,720 MJME) of the three scenarios (**Table 2.9**). This option will have the closest final mean BCS (3.22) to the original mean of 3.0. The potential implications of this feeding approach could result in negative effects on ewe reproductive performance from restricting nutrition for high BCS ewes, as discussed in Section 2.6. However, this would be dependent on the time of the year the ewes are managed in this way, therefore, farmers need to take this into consideration.

It is also important to note that changes in feeding management does not produce a permanent fix for BCS distribution within a flock and the feeding levels will need to be reassessed throughout the year and across each season to maintain ewes within the optimum range. It is also worthy to note that farmers do indirectly select against very low BCS ewes by culling them at the end of the season. A further option is genetic selection to select for optimum BCS.

2.7.2 Genetics

Genetic selection could be used to select for a greater BCS. However, this could potentially have a similar outcome to raising the nutrition of all ewes, to increase overall BCS, in that it would result in increasing the mean BCS genetically and this would have potential impacts on flock total feed demand. Section 2.8 below states that BCS is likely moderately heritable and has a moderate repeatability. This indicates that selecting BCS at one time point will be a moderate indicator for BCS at another time point. The repeatability of changes in BCS has been reported as low by Walkom and Brown (2017), the only authors to explore this. Another option other than selecting for an overall increased BCS could be to select for an optimum BCS.

To achieve an optimum BCS through genetic selection, the variation in BCS of the sire's offspring would ideally be low, therefore, the variation of BCS must be considered. An option could be to select for sires that produce progeny with a mean BCS of 3.0 and with a smaller variance. This would over time, result in a greater proportion of ewes within a close range of BCS 3.0. Variation has been studied in birth weight of sheep (Sae-Lim et al. 2018), birth weight of pigs (Sell-Kubiak et al. 2015), litter size of pigs (Felleki et al. 2012), body weight in Atlantic salmon (Sonesson et al. 2013) and in milk production traits in dairy cattle (Vandenplas et al. 2013). In these studies, a double hierarchical generalized linear model (DHGLM) was used to estimate variance components and breeding values in the residual variance aspect (Rönnegård et al. 2010). However, this has as yet, not been investigated in BCS to this authors knowledge. Sell-Kubiak et al. (2015) compared DHGLM with conventional individual linear model analysis and reported they were comparable. Therefore, it is possible that these same methods could be applied to BCS and selection indexes could be determined to select for sires with a smaller variance. If uniformity in BCS is heritable, then selection against both very low and very high BCS would be possible.

2.8 Genetic parameters of body condition score

2.8.1 Breed

The New Zealand ewe flock can be divided into three sub-groups including dual-purpose (55.5% of registered ewes), terminal (17.9% registered ewes) and fine wool (13.7% of registered ewes, Beef+Lamb New Zealand 2017). The dual-purpose sheep include but, are not limited to, breeds such as the Romney, Coopworth and Perendale and composite based on these (Corner-Thomas et al. 2013) which have a focus on maternal ability and growth. Fine wool breeds merino and merino crossbreds focus on wool growth (Sutherland 2018).

There is a difference in fat deposition and metabolism sites between breeds (Russel 1984a; Frutos et al. 1997). Fat tail breeds hold more fat in the tail whereas dairy sheep breeds hold more fat around the internal organs compared to Romney based breeds (Russel 1984a; Frutos et al. 1997; Chay-Canul et al. 2011). Therefore, breed needs to be included when considering genetic effects of BCS. In New Zealand around 85% of maternal sheep are Romney or Romney based breeds (eg composites, Perendale, Coopworth) and around 8% Merino or Merino-cross (eg ½ breed and Corriedale, Beef+Lamb New Zealand 2019a). Therefore due to the site of fat deposition and metabolism showing little difference between these breeds, breed will not be considered further in this review (Frutos et al. 1997).

2.8.2 Heritability of body condition score

Heritability (h^2) is a parameter reflecting the proportion of a population's phenotypic variance for a trait that can be attributed to the genetic variance between the individuals .

Heritability can be described in terms of the genetic and residual variance components as:

$$h^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_e^2}$$

where σ_g^2 is the genetic variance and σ_e^2 is the residual variance.

If there are repeated measures on the same animal, then the residual variance can be partitioned into a component common to the repeated measures and a component unique to each measure:

$$h^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_{pe}^2 + \sigma_e^2}$$

where $\sigma_{pe}^2{}^2$ is the permanent environment variance and $\sigma_e^2$is the residual variance unique to any measure.

The value of heritability indicates the strength of the relationship between phenotype and genotype, and therefore reflects the degree to which a population can respond to mass selection for a trait. To breed for animals which express the desired trait, for example selecting for greater BCS ewes, may result in greater fat reserves at key times of the year. Selection response to low heritabilities will be low and sometimes more genetic gain can be made by indirect selection for another trait that has a high genetic correlation with the target trait (e.g indirect selection for lower fly strike by selecting for breach bareness, Pickering et al. 2012). In contrast, greater heritability is likely to result in somewhat faster genetic gain than a trait with low heritability.

A summary of previously reported heritabilities for BCS is shown in Table 2.10. There are a range of heritabilities reported in a number of breeds from low to moderately heritable (0.08-0.30), indicating that genetic change can be made using mass selection but that progress will likely be slow. Only two of these studies are New Zealand based and are focused on live weight (Shackell et al. 2011) and ewe rearing performance (Everett-Hincks and Cullen 2009), therefore a New Zealand study focusing on BCS is needed.

The heritability of the change in BCS is negligible to low (0.00-0.06) indicating that there is little scope for selection of change (Walkom et al. 2014b; Walkom et al. 2014c; Walkom and Brown 2017; Macé et al. 2018a). However, this has only been carried out in Australian and French sheep populations. It would likely be beneficial to know if the sheep breeds in New Zealand displayed a similar relationship

2.8.3 *Repeatability of body condition score*

Repeatability reflects the strength of the relationship between different measurements of the same trait (Lessells and Boag 1987). It is a measure of the variation between records (repeated phenotypic values) that can be explained by permanent effect such as breeding values and permanent environmental effects. The greater the repeatability of a trait, the higher the likelihood of an animal having a similar ranking in the population to that ranking obtained from previous records (Wolak et al. 2012). Repeatability is useful as a measure of the within-individual consistency of a trait. Repeatability must be at least as large as the heritability and is defined by the following equation using the same abbreviations as above:

$$t = \frac{\sigma_g^2 + \sigma_{pe}^2}{\sigma_g^2 + \sigma_{pe}^2 + \sigma_e^2}$$

Repeatability of BCS in previous studies has been reported as low to moderate in ewes (0.12-0.49, Table 2.10). Walkom and Brown (2017) reported a moderate repeatability of 0.49 in Australian merino sheep, while Shackell et al. 2011 reported a moderate repeatability (0.30) in New Zealand crossbred sheep. This means that there is moderate consistency within ewe BCS throughout the year. The lower repeatabilities reported by Walkom and Brown (2017) were calculated for merino ewes only.

Table 2.10. Summary of studies which calculated ewe body condition score (BCS, scale 1-5) heritability (h^2) and repeatability (t) with standard errors in brackets.

Reference	Breed	h^2	t
Mating			
Mekkawy et al. (2009)	Scottish Blackface and Hardy Speckled Face	0.24 (0.12-0.37)*	
Shackell et al. (2011)	Traditional and composite breeds	0.28 (0.02)	0.30 (0.01)
Brown et al. (2017)	Merino ewes	0.11 (0.03)	0.22 (0.03)
Walkom and Brown (2017)	Multiple breeds, predominantly Merino	0.25 (0.01)	0.28-0.49
Pregnancy Scanning			
Everett-Hincks and Cullen (2009)	Romney, Coopworth and Texel	0.16 (0.02)	0.31-0.34 (0.02)
Shackell et al. (2011)	Traditional and composite breeds	0.30	0.39 (0.01)
Walkom (2014)			
Walkom et al. (2016)	Lambpro composite	0.17 (0.03)	0.37 (0.02)
Walkom and Brown (2017)	Multiple breeds	0.29 (0.02)	0.28-0.49
Pre-Lambing			
Borg et al. (2009)	Targhee	0.13-0.15	
Everett-Hincks and Cullen (2009)	Romney, Coopworth and Texel	0.18 (0.02)	
Shackell et al. (2011)	Traditional and composite breeds	0.21 (0.01)	0.27 (0.02)
Walkom and Brown (2017)	Multiple breeds, predominantly Merino	0.28 (0.02)	0.28-0.49
Weaning			
Borg et al. (2009)	Targhee	0.13	
Shackell et al. (2011)	Traditional and composite breeds	0.30 (0.02)	0.41 (0.02)
Walkom et al. (2014b)	Crossbred ewes	0.21-0.26 (0.02)	
Walkom et al. (2014c)	Merino ewes	0.08-0.11 (0.02)	0.12-0.16 (0.02)
Walkom and Brown (2017)	Multiple breeds, predominantly Merino	0.22 (0.02)	0.28-0.49
Post-Weaning			
Walkom et al. (2016)	Lambpro composite	0.17 (0.03)	0.37 (0.02)
Borg et al. (2009)	Targhee	0.15	
Change in BCS			
Walkom and Brown (2017)	Multiple breeds, predominantly Merino	0.03-0.06	
Macé et al. (2018a)	Romane ewes	0.06-0.15	

*95% confidence interval

2.9 Genetic correlations between body condition score, live weight and other production traits

2.9.1 Phenotypic and genetic correlations of body condition score and live weight

A summary of estimates of genetic parameters including heritabilities, genetic and phenotypic correlations between BCS, live weight and production traits is shown in Table 2.11. Body condition score throughout the production cycle (i.e. mating, scanning, lambing and weaning) have been found to be strongly genetically correlated (Shackell et al. 2011; Brown and Swan 2014; Walkom et al. 2014b; Walkom and Brown 2017). High genetic correlations between BCS measurements indicate that there are potentially similar genes influencing BCS at each measurement time point. This could suggest that only one measurement per year would be required for genetic selection, however, this would need to be considered in more than one study (Shackell et al. 2011).

The strong genetic correlation between BCS and live weight indicates that selecting for greater live weight alone and ignoring BCS would actually result in the selected candidates themselves having greater BCS, and there would also be a propensity for greater BCS in subsequent generations. However, the current national evaluation system imposes negative selection pressure on mature liveweight (Sheep Improvement Limited 2017), meaning that ignoring BCS could lead to slow genetic progress in BCS over time if live weight was selected against. Phenotypic correlations of BCS measurements tend to be low to moderate (0.37-0.52, Table 2.11.), indicating that environmental factors have a significant influence on phenotypic BCS values.

2.9.2 Phenotypic and genetic correlations of body condition score with other production traits

The heritability, phenotypic and genetic correlation of BCS with production traits in sheep have been analysed internationally (Table 2.11). Mekkawy et al. (2009) reported that longevity in Mule ewes had a moderate heritability but had a negative genetic correlation (-0.07) with BCS at first mating at 18 months of age. Longevity is the length of the productive life of a ewe and increased longevity results in decreased culling rates and replacement ewe costs (Brash et al. 1994; Mekkawy et al. 2009). This means that BCS could have a negative genetic effect on the longevity of a ewe but more data is required to confirm this.

The genetic correlations between pre-mating BCS in Australian merino ewes and a number of reproduction traits including pregnancy scanning, fertility, fecundity, NLB and NLW have been reported (Brown et al. 2017; Walkom and Brown 2017). There was a strong negative genetic correlation between BCS and these reproduction traits which means that if greater reproduction is selected for, BCS could decrease. To date it appears that there are no genetic correlations reported between BCS and reproduction traits in New Zealand studies. The only genetic correlations reported in a New Zealand study was between BCS and litter survival, birth weight, weaning weight and total litter weaning weight (Everett-Hincks and Cullen 2009). These correlations indicate that BCS and production generally had a negative genetic correlation, with total litter weaning weight (TLW) having the only positive genetic correlation with BCS.

There is a need for more studies on the genetic correlation between BCS and productive performance traits to determine the effect that selecting for one trait could have on the other. This would determine the effect of selection for greater BCS might have on traits such as pregnancy scanning, NLB, NLW, lamb WWT and TLW in New Zealand sheep flocks. This information could be used to determine the best method of incorporating BCS into a selection index.

Table 2.11. Heritability, genetic and phenotypic correlations between potential traits influencing body condition score (BCS). Traits included are BCS as a repeated measure, body condition score change (BCS change), live weight, longevity, greasy fleece weight, pregnancy scanning, fertility, fecundity, number of lambs born (NLB), number of lambs weaned (NLW), litter survival, birth weight, weaning weight (WWT), total litter weaning weight (TLW), fat depth and eye muscle depth (EMD).

Trait	Genetic	Phenotypic	h^2	Reference
BCS measurements	0.74-1.00	0.37-0.52	0.08-0.30	(Everett-Hincks and Cullen 2009; Shackell et al. 2011; Brown and Swan 2014b; Walkom et al. 2014b; Walkom and Brown 2017)
BCS change	-1.45	-1.08	0.03-0.18	(Walkom and Brown 2017; Macé et al. 2018b)
Live weight	0.54 - 0.73	0.53-0.65	0.57-0.66	(Shackell et al. 2011; Brown and Swan 2014b; Walkom et al. 2016)
Longevity	-0.07	0.01	0.27	(Mekkawy et al. 2009)
Greasy fleece weight	-0.60-0.06	-0.05	0.39	(Everett-Hincks and Cullen 2009; Walkom and Brown 2017)
Fibre diameter	0.20-0.33	0.07-0.14	0.88	(Walkom and Brown 2017)
Pregnancy Scanning	0.11-0.41	-0.01-0.17	0.06	(Walkom and Brown 2017)
Fertility	0.12-0.34	0.02-0.56	0.03	(Brown et al. 2017; Walkom and Brown 2017)
Fecundity	0.10-0.24	0.01-0.72	0.08	(Walkom and Brown 2017)
NLB	-0.96-0.41	-0.19-0.84	0.06-0.12	(Borg et al. 2009; Brown et al. 2017; Walkom and Brown 2017)
NLW	-0.15-0.33	-0.13-0.56	0.04-0.08	(Walkom et al. 2016; Brown et al. 2017; Walkom and Brown 2017)
Litter survival	-1.19-0.33	-0.17-0.36	0.01-0.04	(Everett-Hincks and Cullen 2009; Walkom and Brown 2017)
Birth weight	-0.32		0.19	(Borg et al. 2009; Everett-Hincks and Cullen 2009)
WWT	-0.72	0.44-0.69	0.38	(Borg et al. 2009; Everett-Hincks and Cullen 2009; Walkom et al. 2016; Walkom and Brown 2017)
TLW	0.09	0.11	0.12	(Everett-Hincks and Cullen 2009)
Fat Depth	0.60-0.92	0.11-0.16	0.23	(Walkom et al. 2016; Walkom and Brown 2017)
EMD	0.09-0.17	0.09-0.17	0.38	(Walkom et al. 2016; Walkom and Brown 2017)

Change in BCS is an indicator of the nutritional state that a ewe has been in over the period of time since BCS was last measured. Change in BCS throughout the production season has a low heritability (Walkom and Brown 2017; Macé et al. 2018a). To date genetic correlations between BCS change and productive traits have only been reported in Australian merino cross sheep which were low (Walkom and Brown 2017). Walkom and Brown (2017) reported that the BCS change between BCS measurements provided no improvement to the current practice of using the static BCS measurements. However, BCS profiles or the gain/loss in BCS across a season or year have not been modelled or genetically evaluated. This would consider all changes across the year, not just the change across a small period of the production cycle.

Another aspect of BCS that could be investigated is the genes associated with BCS. Genotyping has been undertaken in New Zealand sheep (Jiang et al. 2014), but the genes and mutations associated with variation in BCS have not been identified or characterised.

2.10 Selection Objectives

Ram breeders use selection objectives to guide genetic improvement of the flock through the weighted importance of each traits to the breed (Blair and Garrick 2007). The ram breeder then sells rams to the commercial farmers on the basis of these selection objectives. Merino Select is the Australian sheep database that focuses on wool traits (Meat & Livestock Australia Limited and Australian Wool Innovation 2009). Sheep Improvement Limited (SIL), established in 1999, is the national New Zealand sheep industry's performance recording and genetic evaluation database. It follows three previous breeding schemes; National Flock Recording Scheme (est. 1967), Sheeplan (est. 1976) and Animalplan (est. 1988) (Young and Wakelin 2009; Sheep Improvement Limited 2020). There are numerous selection traits available on this database for the 'Terminal', 'Maternal' and 'Mid-micron wool' sheep breeder. It currently provides an across-flock genetic evaluation (SIL-ACE) which includes over 3 million animals (Young and Wakelin 2009; Sheep Improvement Limited 2020).

The selection objective of the New Zealand sheep meat industry aims to improve the genetic ability of ewes to produce and rear two lambs successfully to weaning and then are finished for slaughter. To achieve this objective, a selection index called the New Zealand Standard Maternal Worth Index (NZMW) was developed to represent how much a ram is valued in cents above an average stud sheep in the year 1995.

The NZMW is calculated as:

$$\text{NZMW} = \sum BV_i \ EV_i$$

Where BV_i is the breeding value for trait i and EV is the corresponding economic value. The traits considered in NZMW are lamb growth, adult size, reproduction, survival and wool (**Error! Reference source not found.**, Core Traits, Sheep I mprovement Limited 2019), however, there are other traits recorded in the database that can be tailored for additional traits of interest. The economic values in 2019 measured in cents per lamb born were 122 for direct weaning weight (WWT_d), 140 for maternal weaning weight (WWT_m), 467 for carcass weight, -147 for mature ewe live weight, non-linear for NLB, 11274 for survival, 341 for lamb fleece weight, 153 for hogget fleece weight and 443 for adult fleece weight (Sheep Improvement Limited 2019c). The negative economic weighing on mature ewe live weight and the positive weighting on reproduction and survival, aims to increase production while maintaining flock ewe live weight by rewarding each trait by its relative economic value. Live weight and BCS have a high genetic correlation (Table 2.11) which means that BCS gain is being restricted in making genetic progress by the negative weighting on live weight. Previous sections of this review have shown that BCS is important, however, it is not currently included in the core traits of the NZMW or MerinoSelect. As a result, BCS has only recently been included in the custom selection indices for a small number of SIL flocks and it is not currently included in Merino Select.

Sheep Improvement Limited calculates EBVs for BCS from BCS recorded at mating (Sheep Improvement Limited 2016b). The analysis adjusts for NLW in the previous year. Ultrasound eye muscle measurements (eye muscle depth, eye muscle width and fat depth over the eye muscle) are also used as predictors for the BCS EBV. The ultrasound measurements can be added to the estimate of BCS EBV due to the moderate correlation with BCS (Walkom et al. 2017). The BCS index weighting is based on energy and feed costs of gaining a unit of BCS minus energy and feed costs released by a unit of BCS. The final economic value is defined by the difference in cost between ewes that are 1 BCS different at mating (Sheep Improvement Limited 2016b).

2.11 Genetic Trends

A genetic trend is an average of the genetic merit EBV across generations and identifies the progress in change of a specific trait over time. It is often visualised as a graph and can provide insight as to the rate of genetic gain for a specific trait over time. A genetic trend can be useful to ensure that while a combination of traits are selected for simultaneously, each individual trait is making satisfactory progress.

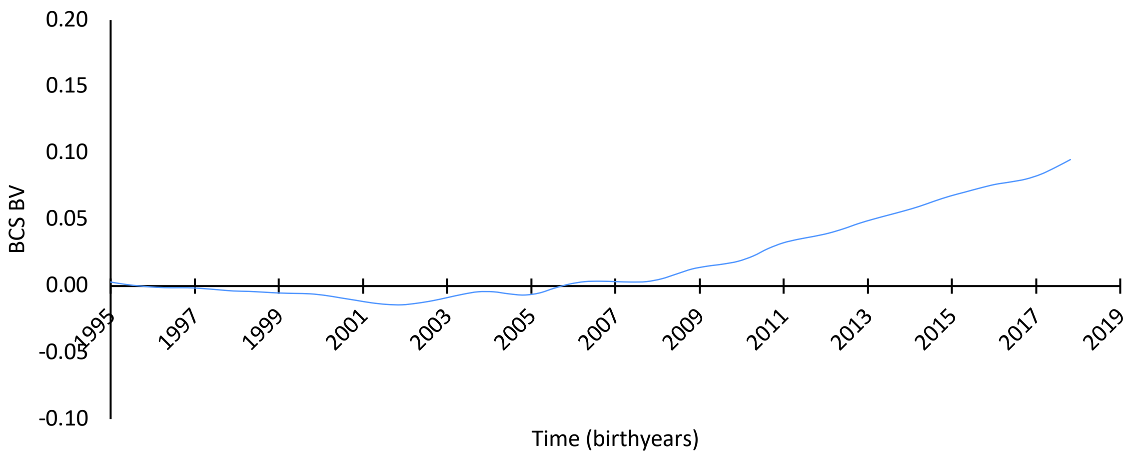


Figure 2.4. Trend in breeding value (BV) for body condition score (BCS) in New Zealand dual-purpose sheep (adapted from Sheep Improvement Limited 2019b, GE Analysis #36903 23/09/2019).

The genetic trend of BCS, relative to ewe in 1995, has been reported by Sheep Improvement Limited (2019b), shown in Figure 2.4. The genetic trend of BCS prior to 2002 followed a slight negative trend and post-2008 there has been a steady increase. The EBV for BCS was included in SIL from 2015. The average standard deviation of BCS for the New Zealand sheep flock has been reported as 0.60 (Shackell et al. 2011), therefore, the genetic trend increase is 0.17 of a standard deviation. The increase in BCS EBV could also be due to selection pressure being placed on traits that are strongly genetically correlated with BCS, however, there is limited information around the genetic correlations between BCS and production traits. As previously mentioned in Section 2.9, BCS and live weight are strongly genetically correlated (Table 2.3), as are fat depth and eye muscle depth. Selection for increased fat depth and eye muscle depth may also increase BCS, however, it is unknown what the effect of selecting for increased reproductive performance could have on BCS and vice versa.

Although Figure 2.5 starts at 1995, selection and genetic trend recording occurred prior to this. Mature liveweight EBV has been increasing since the beginning of trait recording in the national sheep recording scheme (now called Sheep Improvement Limited). Recently it had become apparent that ewe liveweight is not a good indicator of sheep production (Figure 2.5). The economic value placed on adult live weight, or size, as referred to by Sheep Improvement Limited (2019a), has been negative since 1995 and over time the magnitude of the negative weighting has increased to -500 cents in January 2018.

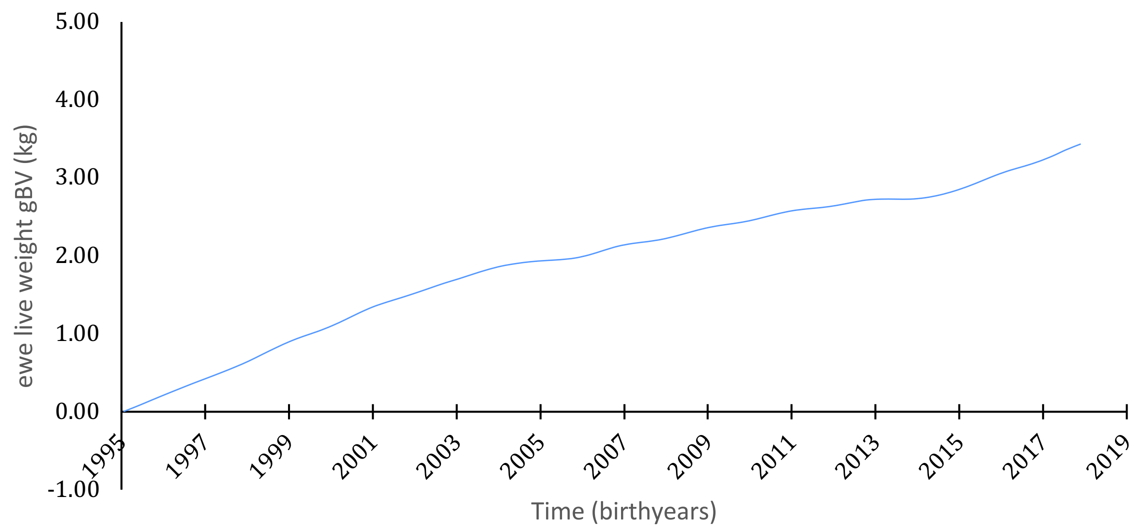


Figure 2.5. Trend in breeding value (BV) for mature ewe live weight in New Zealand sheep (adapted from Sheep Improvement Limited 2019a, GE Analysis #36903 23/09/2019)

2.12 Body condition score profiles of BCS gain and loss throughout the year on sheep production

Research and guidelines in regards to BCS have focused to date on a single time point (as indicated in Tables 2.4 to 2.6; Kenyon and Cranston 2017). However, this differs from reality for individuals and flocks as BCS increases and decreases throughout the year due to environmental and physiological factors (Curnow et al. 2011; Macé et al. 2019).

2.12.1 Phenotypic body condition score profiles

A BCS profile can be defined as the pattern of BCS which each individual animal takes throughout one production cycle as the animal mobilises and deposits body fat. The profiles of ewe BCS in a population of Romane ewes has been analysed as clusters by Macé et al. (2019) and three different groups were identified across three production cycles. To this authors knowledge, there are currently no known studies reporting the productive differences between the different phenotypic BCS profiles.

Target profiles have been developed (i.e. Figure 2.6, where a BCS of 3.5 is recommended at mating and mid-pregnancy Russel 1984a; Russel 1984b; Hocking-Edwards et al. 2011; Kenyon and Cranston 2017). It was also recommended that BCS does not drop below 2.5 and that the ewe should not lose more than 1.0 BCS during lactation (Cannas 2002). Even though there have been target BCS profiles recommended, these are theoretical and to date it appears no one has tested the impact of the various BCS profiles on phenotypic performance.

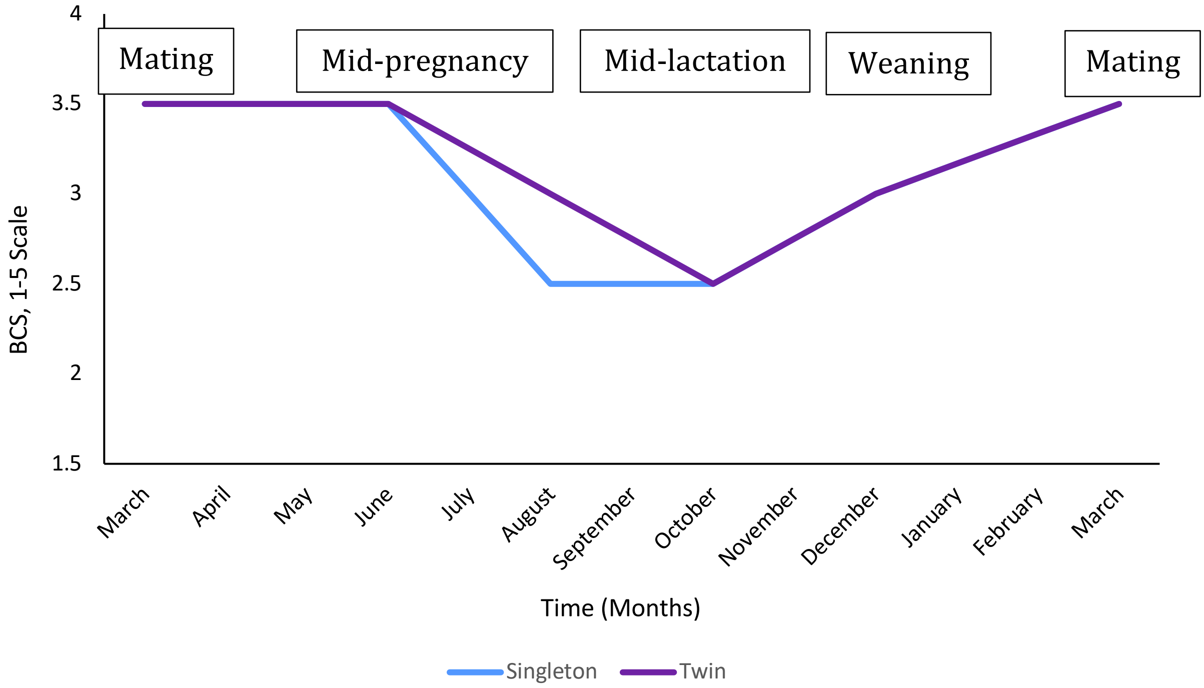


Figure 2.6. Stylised ideal body condition score (BCS) profile for singleton and twin bearing/rearing ewes (adapted from Kenyon and Cranston 2017).

2.12.2 Modelling body condition score

Previously modelled profiles or curves in dairy cattle using predicted values have included growth (Handcock et al. 2018), lactation (Roche et al. 2006; Arnal et al. 2018) and liveweight curves (Handcock et al. 2018). Body condition score profiles have been modelled in dairy cattle and are strongly influenced by milk production (Roche et al. 2006). Live weight and milk production can be often measured daily on dairy farms, and BCS monthly. Conversely, BCS on sheep farms, if measured at all, is generally only measured at four key times of the year (Kenyon et al. 2014; Walkom et al. 2014b). These four time periods include prior to mating, mid-pregnancy, prior to lambing and weaning (Walkom et al. 2014b; Walkom and Brown 2017).

If the BCS profile were to be modelled, then the BCS could be predicted at any day across the production cycle. This could be used to identify animals that follow similar patterns of gain and loss throughout the year. The benefit of modelling BCS profiles would be identifying the optimal profile for all ewes to follow and then using management to try and ensure ewes follow this optimal profile. This approach is likely to improve feed efficiency.

2.12.3 Genetic body condition score profiles

A few studies have estimated genetic parameters of BCS change (see Section 2.9, Walkom and Brown 2017; Macé et al. 2018a; Macé et al. 2018b), but none considered the change across the whole production cycle i.e. a yearly BCS profile. There may be merit in examining the genetic BCS profile over time to identify groups of animals that potentially require different management to meet their genetic potential for production. The genetic parameters of a BCS profile, to the authors knowledge, have not been identified.

2.13 Conclusions

Body condition score measured on 1-5 scale in sheep can be used to determine the nutritional status of the individual. It is well-documented that individual BCS measurements are associated with productive performance (Kenyon et al. 2014). Less well-documented is the effect of changes in BCS between the individual BCS measurements have on production. Further, there are limited New Zealand studies reporting the genetic parameters between BCS and production traits and no studies examining the BCS profile. If this was known the farmer would be able to identify the most productive ewes by the BCS profile that the ewe has.

A BCS estimated breeding value has been added to the NZMW SIL Index, but there was little information in NZ published on the genetic correlations between BCS and production traits. The genetic parameters between BCS and production traits will provide valuable information as to traits which are genetically correlated with BCS and how this could affect genetic progress of BCS. With this knowledge sheep breeders and commercial farmers would be able to make a more informed decision for including BCS in their selection program.

Therefore, the aims for this thesis are:

a) Describe the relationships between BCS and production traits in sheep to establish a better understanding of the influence of BCS on productive performance (Chapter 3).
b) Explore change in BCS throughout the production cycle and its effect on productive performance (Chapter 3 & 6).

c) Determine the genetic parameters of BCS, BCS change and production traits (Chapter 4 & 5).
d) Identify and characterise BCS profiles in a population of ewes (Chapter 6).
e) Evaluate the effects of phenotypic BCS profiles on sheep production (Chapter 6).
f) Determine the genetic variances of BCS profiles (Chapter 7).

3 Associations of body condition score and change in body condition score with lamb production in New Zealand Romney ewes

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3.1 Abstract

Body condition score (BCS) is an on-farm subjective measurement used to inform feed management decisions in sheep. This study determined the associations of BCS and changes in BCS on production. Ewe BCS was recorded four times annually in a flock of 2,534 Romney ewes aged between one to five years that were first bred at eight-months of age. Production was measured as the number of fetuses scanned (NLS), number of lambs weaned (NLW), average weight of lambs weaned (avWWT) and total weight of lamb weaned (TLW). Ewe BCS was greatest at lambing and lowest at weaning. At pregnancy scanning (at an average of 75 days of pregnancy), two weeks prior to lambing, and at weaning, BCS ≥4.5 was associated with the lowest NLS and NLW, but the greatest avWWT. Ewes with a BCS ≤2.5 at weaning were associated with the greatest TLW, suggesting these ewes had utilised their stored body fat to achieve high milk yields. Ewes that decreased BCS between lambing and weaning produced greater ($P<0.05$) TLW compared with ewes which maintained or gained BCS indicating their body reserves were acting as a buffer for milk production. The results of the current study showed that there was an effect of BCS on NLS, NLW, avWWT and TLW. The change in BCS from scanning to weaning is an important determinate of NLW, avWWT and TLW. A further study with more focus on the change in BCS is, therefore, warranted.

3.2 Introduction

The New Zealand sheep flock was 27.6 million in 2016 distributed evenly between the North and South Islands. In 2016, the average lambing percentage was 130% and average lamb carcass weight was 18.6 kg (Beef+Lamb New Zealand 2017). For the majority of sheep farmers, lamb sales are their main source of income (Beef+Lamb New Zealand 2018). The amount of saleable lamb produced is driven by both the total number and weight of lambs weaned (Morel 2006; Young et al. 2010). Sheep production is influenced by the body reserves of the ewe by allowing for energy to be stored as fat to be used during pregnancy and lactation to grow the lambs.

Body reserves are estimated using body condition score (BCS) which is a subjective estimate of both fat and muscle of the animal (Van Burgel et al. 2011; Kenyon et al. 2014). Ewe BCS is a better indicator of body reserves than is live weight (Russel et al. 1969; West et al. 1990; Dunn & Moss 1992). It has been suggested that feed management decisions should be based on BCS, rather than on live weight (Dechow et al. 2001).

A strong relationship has been reported between ewe BCS at a given time and her reproductive performance. (Kenyon et al. 2014). The measurement of BCS allows for intervention in nutritional management by separating ewes and either restrict, maintain or increase feeding levels to increase productivity. There is limited information however, on the effect of BCS on the weight of the lamb at weaning. To these authors knowledge there is no published data on the effect of change of BCS during the year on a number of production traits. The present study aim was to determine the effect of BCS and BCS change on production being that greater BCS would result in greater production.

3.3 Materials and methods

3.3.1 Animals

The study included 2,534 Romney ewes first bred at eight-months of age. Ewe data were obtained from Freestone, a Focus Genetics flock that was commercially managed. Birthyear ranged from 2008-2016, and therefore ewe age ranged from one to five years. Ewes had both sire and dam data recorded and DNA was collected from the ewes and their lambs to determine parentage. The NLS was based on the number of lambs recorded at pregnancy diagnosis using ultrasound scanning (as per SIL database procedure) and from ranged one to six. Rearing rank or NLW was recorded as number of lambs present at weaning and ranged from one to six.

3.3.2 Measurements

Ewe BCS measures were recorded four times per year between 2009-2017, on a 1-5 scale (Jefferies 1961) with 0.5 increments. The four time points were; prior to mating in April (mating), at pregnancy diagnosis in July (scanning), prior to lambing in August (lambing) and at weaning in January (weaning). Ewe live weight was also recorded at mating and lambs were weighed at weaning (avWWT). Pregnancy scanning was recorded at approximately 75 days of pregnancy and was recorded as NLS from zero through to six. Number of lambs born was not recorded. The number of lambs present at weaning (NLW) combined with the lamb weaning weight was used to determine TLW.

Data were cleaned and traits were tested for normality as described in Chapter 5 for all four Focus Genetics flocks. This was to remove BCS records that were not whole or half scores between 0-5, ewes that had negative or zero RR values and one- and five-year-old ewes.Ewes at each measurement period were classified into the following BCS groups ≤2.5, 3.0, 3.5, 4.0 and ≥4.5 as there were smaller numbers at the extreme BCS values. Change in BCS were classed in terms of gain in BCS, loss in BCS or maintained BCS between consecutive measurement periods. The change between measurements was a gain or loss that ranged between 0.5 to 2.0 BCS.

3.3.3 Statistical analysis

Statistical analyses were undertaken using SAS 9.4 (SAS Institute Inc, Cary NC, USA). The descriptive statistics (Table 3.1) were obtained using the MEANS procedure. Data analysis models were created for each trait separately. Fixed effect models were determined using the general linear model procedure (GLM). Fixed effects fitted included; season, age, age at first lambing (AFL), AOD, birth-rearing rank of the ewe (BR_RR). Fixed effects were tested for significance in the model and AOD was removed from the final model. Analysis of variance for NLS, NLW, avWWT and TLW were performed at each measurement period of BCS using the SAS GLM procedure with a model that included the effects of BCS class, season, age, age at first lambing, birth-rearing rank of the ewe. Least-squares means of NLS, NLW, avWWT and TLW for each BCS class within each measurement period were obtained and used for multiple mean comparison using the Fisher's least-significant-difference test as implemented in the LSMEANS option of the GLM procedure. Effects of change in BCS from mating to weaning on NLS, NLW, avWWT and TLW were evaluated using the GLM procedure with a model that included the effects of season, age, AFL and scan-rearing rank of the ewe.

3.4 Results

Descriptive statistics for BCS, live weight at mating and production traits are presented in Table 3.1. Ewe BCS was highest at lambing and lowest at weaning.

Table 3.1. Summary statistics for BCS of New Zealand Romney ewes at mating, pregnancy scanning, prior to lambing and weaning, mating live weight, number of lambs scanned (NLS), number of lambs weaned (NLW), average lamb weaning weight (avWWT) and total weight of lamb weaned (TLW).

Trait	n	Records	Mean	SD	Min	Max
Mating BCS	2324	4553	3.48	0.46	1.5	5
Scanning BCS	2268	6578	3.45	0.47	1.5	5
Lambing BCS	1514	2908	3.58	0.46	1.5	5
Weaning BCS	2534	5465	3.05	0.62	1	5
Mating live weight (kg)	2040	4554	72.85	8.85	44.8	108.5
NLS	2533	7543	1.97	0.88	0	3
NLW	2010	6164	1.53	0.84	0	3
avWWT (kg)	1450	5020	33.21	6.92	10	58
TLW (kg)	1462	5053	54.77	21.24	13.2	157

Ewes of BCS ≥4.0 at mating had a greater ($P<0.05$) NLS compared with ewes with a BCS of 3.0 (Table 3.2). However, BCS at mating had no effect on NLW, avWWT or TLW. Ewe BCS at scanning influenced all production traits ($P<0.05$). Ewe BCS at scanning of ≥4.5 had lower NLS, NLW and TLW but a greater avWWT. Ewe BCS at lambing and weaning was associated with NLW, avWWT and TLW ($P<0.05$). Ewes with a BCS ≤4.0 at lambing had a greater TLW than ewes with BCS ≥4.5 (Table 3.2). There was no effect of BCS at the previous weaning on production traits (results not shown).

Table 3.2. Least-squares means (± SEM) for number of lambs scanned (NLS), number of lambs weaned (NLW), average lamb weaning weight (avWWT) and total weight of lamb weaned (TLW) of New Zealand Romney ewes of different classes of body condition score (BCS) at mating, scanning, lambing and weaning.

Period	BCS class	n	NLS	NLW	avWWT (kg)	TLW (kg)
Mating	≤2.5	214	2.40±0.06^{ab}	1.76±0.07	35.9±0.6	64.0±2.1
	3	1191	2.38±0.03^{b}	1.76±0.04	35.9±0.4	63.2±1.2
	3.5	2192	2.42±0.03^{ab}	1.76±0.04	36.1±0.3	63.5±1.1
	4	934	2.47±0.03^{a}	1.72±0.04	36.5±0.4	63.2±1.2
	≥4.5	224	2.49±0.05^{a}	1.73±0.08	36.8±0.7	65.2±2.2
Scanning	≤2.5	150	2.42±0.06^{ab}	1.84±0.07^{a}	32.8±0.6^{c}	56.7±1.7^{ab}
	3	901	2.42±0.05^{a}	1.83±0.06^{a}	33.6±0.5^{b}	58.0±1.5^{a}
	3.5	2491	2.36±0.05^{bc}	1.82±0.06^{a}	33.9±0.5^{ab}	58.0±1.4^{a}
	4	1175	2.41±0.05^{ab}	1.80±0.06^{a}	34.5±0.5^{b}	57.5±1.5^{ab}
	≥4.5	250	2.29±0.07^{c}	1.64±0.09^{b}	34.9±0.7^{a}	54.2±2.2^{b}
Lambing	≤2.5	45		1.76±0.10^{a}	30.5±0.8^{d}	56.2±2.4^{ab}
	3	317		1.81±0.06^{a}	31.8±0.5^{cd}	58.2±1.7^{a}
	3.5	1134		1.74±0.05^{a}	32.1±0.5^{c}	56.2±1.4^{ab}
	4	693		1.56±0.06^{b}	33.3±0.5^{b}	53.5±1.5^{b}
	≥4.5	105		1.36±0.08^{c}	35.7±0.7^{a}	47.7±2.2^{c}
Weaning	≤2.5	1032		2.15±0.05^{a}	32.7±0.5^{c}	64.7±1.3^{a}
	3	1330		1.89±0.05^{b}	34.4±0.5^{b}	59.3±1.3^{b}
	3.5	1099		1.63±0.05^{c}	35.5±0.5^{a}	53.6±1.3^{c}
	4	358		1.25±0.06^{d}	36.0±0.5^{a}	45.2±1.6^{d}
	≥4.5	101		0.88±0.07^{e}	37.0±0.9^{a}	42.4±2.5^{d}

$^{a, b, c}$ Means with different superscript within column at each measurement time are significantly different (P<0.05).

A change in BCS from the previous weaning to mating was associated with all production traits (Table 3.3). A gain in BCS between weaning and mating resulted in greater NLS, NLW and TLW, but lesser WWT. Ewe BCS change from mating to scanning was associated with NLS but not NLW, avWWT or TLW. A gain in BCS in this period was associated with a lower NLS (P<0.05). Ewe BCS change between scanning and lambing was associated with all production traits. A gain in BCS between scanning and lambing was associated with a lower NLW and TLW (P<0.05), but a greater (P<0.05) avWWT than ewes that maintained or decreased BCS. Ewe BCS change from lambing to weaning also affected all production traits. A loss in BCS in this period was associated with a greater (P<0.05) NLW and TLW than ewes that gained BCS across the same period, but a lower avWWT (P<0.05).

Table 3.3. The effect of losing, maintaining or gaining body condition score (BCS) from previous weaning to mating, mating to scanning, scanning to lambing and lambing to weaning of New Zealand Romney ewes on number of lambs scanned (NLS), number of lambs weaned (NLW), average litter weaning weight (avWWT), total weight of lambs weaned (TLW) (Least-squares means ± SEM).

Time period	BCS change	n	NLS	NLW	avWWT	TLW
Weaning to mating	loss	273	$2.20±0.05^{c}$	$1.27±0.06^{c}$	$38.1±0.6^{a}$	$52.6±1.8^{c}$
	maintain	880	$2.37±0.04^{b}$	$1.66±0.05^{b}$	$36.7±0.4^{b}$	$61.6±1.3^{b}$
	gain	1273	$2.48±0.04^{a}$	$1.88±0.05^{a}$	$36.5±0.4^{b}$	$67.0±1.2^{a}$
Mating to scanning	loss	875	$2.54±0.03^{a}$	1.77±0.05	36.0±0.4	64.1±1.3
	maintain	2310	$2.44±0.03^{b}$	1.75±0.04	36.1±0.3	63.4±1.1
	gain	1466	$2.38±0.03^{c}$	1.74±0.04	36.4±0.4	62.9±1.2
Scanning to lambing	loss	409		$1.93±0.09^{a}$	$33.1±0.8^{b}$	$64.5±2.4^{a}$
	maintain	882		$1.88±0.07^{a}$	$33.9±0.7^{b}$	$64.7±2.0^{a}$
	gain	686		$1.65±0.08^{b}$	$35.2±0.7^{a}$	$59.2±2.1^{b}$
Lambing to weaning	loss	1173		$1.94±0.07^{a}$	$34.2±0.7^{b}$	$65.0±2.0^{a}$
	maintain	461		$1.59±0.08^{b}$	$35.5±0.7^{a}$	$57.3±2.2^{b}$
	gain	177		$1.10±0.09^{c}$	$36.3±0.8^{a}$	$48.7±2.6^{c}$

$^{a, b, c}$ Means with different superscript within column at each measurement period are significantly different (P<0.05).

3.5 Discussion

The results showed that BCS at mating and scanning were positively associated with NLS at pregnancy diagnosis. It has previously been reported that BCS at mating had a plateauing relationship between BCS on NLS up to a BCS of 2.0-3.0 (Kenyon et al. 2004b; Kleemann & Walker 2005). Molina et al. (1994) reported a positive linear relationship up to BCS 2.0-3.0. In the current study, the lowest BCS group was 2.5, so it is possible that the effect of the lower BCS ewes was not apparent. In contrast, Aliyari et al. (2012) reported a lower fertility rate in ewes with a BCS of >3.5 compared with those with BCS of 3.0 in which fertility was greatest.

Ewe BCS at mating was not associated with avWWT. This finding is in agreement with previous studies Al-Sabbagh et al. (1995), Aliyari et al. (2012) and Verbeek et al. (2012). It is not surprising that mating BCS does not impact on avWWT as there are numerous environmental factors between mating and weaning that influence avWWT including, but not limited to, feed availability, weather and stocking rate. In the current study, lambing BCS was positively associated with avWWT. The results of the current study were in agreement with Molina et al. (1991), however, Karakuş and Atmaca (2016) (2.5-3.5) reported in Norduz ewes and Corner-Thomas et al. (2015) (1.5-2.5) in Romney crossbred ewes, reported that there was no effect of BCS at lambing on avWWT.

The most important trait for farm income is TLW, which is a measure that combines both lamb survival and live weight. The TLW was not influenced by BCS at mating, but a greater BCS at scanning, lambing and weaning was generally associated with a lower TLW. The TLW was heavily influenced by NLW therefore tends to show the same patterns as NLW. This effect has been reported previously by Mathias-Davis et al. (2011). In their review of BCS Kenyon et al. (2014) suggested that although there has been a general positive relationship between BCS and avWWT, there is a plateau above which no further increase in production is seen. This means that ewes with a lower BCS at weaning appear to have used body reserves to feed their multiple lambs, and due to rearing multiple lambs, their TLW is greater.

An increase in BCS from the previous weaning to mating resulted in greater NLS, NLW and TLW but lower avWWT, indicating that it is important for the ewe to be fed to increase BCS during this time. The change in BCS between mating and scanning was associated with NLS but not with NLW, avWWT or TLW. Ewes that gained BCS between scanning to lambing and lambing to weaning generally had lower NLW and TLW, but greater avWWT. The increased avWWT was not great enough to compensate for NLW when TLW was calculated. The degree of the loss of condition from scanning to weaning is possibly a reflection of the number of lambs the ewe carried and reared. A ewe with more lambs will use more BCS to ensure adequate milk for the lambs.

Combined, these results suggest that it is important for the farmers to monitor BCS at scanning, lambing and weaning, and to ensure the ewes do not exceed BCS 4.0 to achieve maximal TLW. Limitations of the current study are that the feeding management was unknown, therefore, it is difficult to determine if loss in BCS is due to feeding levels or milk production (Peterson et al. 2006). High milk yields are associated with high lamb growth rates (Snowder and Glimp 1991). In addition, a single BCS measurement does provide evidence for the potential production of the ewe, however, the profile of BCS change over a season may be a better indicator of production. The current study ewes had above average live weight, therefore it would be interesting to see if the same relationships existed in a flock of lighter ewes.

3.6 Conclusions

The results of the current study showed that for these breeds and location there was an effect of BCS on NLS, NLW, avWWT and TLW. It is recommended that farmers aim for a BCS of 3.0 at mating through to scanning and to not exceed BCS 3.5 at lambing, however, it is key that the ewe has enough condition to be able to drop to a BCS of 2.5 at weaning. The change in BCS from both previous weaning to mating and scanning to weaning are important determinates of NLW, avWWT and TLW. A further study with more focus on the change in BCS is, therefore, suggested.

4 Genetic and phenotypic correlations between production traits and adult body condition scores in New Zealand Merino ewes

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Tait IM, Kenyon PR, Garrick DJ, Pleasants AB, Hickson RE. 2018. Genetic and phenotypic correlations between production traits and adult body condition scores in New Zealand merino ewes. New Zealand Journal of Animal Science and Production 78: 71-75.

4.1 Abstract

Genetic and phenotypic correlations between adult body condition scores (BCS) throughout the production cycle and eye muscle depth, fat depth, two-year-old greasy fleece weight, fibre diameter, staple length and staple strength were estimated from 2,007 pedigree-recorded Merino ewes born between 2013 and 2015. The heritability estimates of BCS at mating, scanning, lambing and weaning were 0.66, 0.39, 0.46 and 0.32 respectively. The heritability estimates for yearling greasy fleece weight, fibre diameter and staple length were 0.65, 0.86 and 0.73 respectively, and all these traits were positively genetically correlated with BCS. The genetic correlations among the four BCS measurements ranged from 0.39-0.83, while the phenotypic correlations ranged from 0.22-0.45. Genetic correlations between BCS and fat depth ranged from 0.67 to 0.83. Given the high heritability of BCS and high genetic correlations between BCS measurements, there is clear scope for selection to alter BCS. Mating appears to be the best time to record BCS for genetic selection, as it had the greatest heritability estimate and the greatest genetic correlations with ultrasound measurements of fat depth and eye-muscle depth and all wool traits except fibre diameter coefficient of variation and greasy fleece weight.

4.2 Introduction

Body condition score (BCS) in sheep is a practical management tool used to measure nutritional status (Jefferies 1961). The advantages of BCS include its ability to identify animals in a state of low nutrition, low cost, ease of measurement and value in comparing animals independent of their live weight and/or gut fill. The BCS is assessed subjectively using a 1-5 scale (Jefferies 1961) in which one is emaciated and five is obese. It has been well documented that BCS of ewes was associated with a number of productive traits (Gunn et al. 1991a; Gunn et al. 1991b; Kenyon et al. 2012a; Kenyon et al. 2014) including fleece traits such as greasy fleece weight and fibre diameter (Walkom & Brown 2017).

Sheep farmers in New Zealand can use genetic selection to improve profitability. New Zealand Merino farmers use the Australian Merino database MerinoSelect (Meat & Livestock Australia Limited and Australian Wool Innovation 2009). Traits in the current MerinoSelect evaluation include body weight, eye muscle depth, fat depth, greasy fleece weight, clean fleece weight, fibre diameter, coefficient of variation of fibre diameter, staple strength, scrotal circumference and worm egg count. The wool traits which are generally accepted to be important in Merino flocks are fibre diameter and clean fleece weight. A breeding value for BCS has recently been made available for dual-purpose sheep in NZ, but the trait has not yet been included in the MerinoSelect evaluation.

Heritability estimates of BCS have been reported for both Australian Merino ewes and New Zealand crossbred ewes and ranged from 0.08 to 0.30 (Everett-Hincks & Cullen. 2009; Shackell et al. 2011; Walkom et al. 2014a; Walkom et al. 2014b; Walkom et al. 2016; Brown et al. 2017; Walkom & Brown. 2017). Heritability estimates of BCS have not been reported to date for New Zealand Merinos.

Walkom and Brown (2017) reported that the genetic correlations among lamb growth traits and ewe adult BCS in Australian crossbred ewes were high, but the genetic correlations with lamb carcass traits were only moderate. In NZ crossbred sheep, the genetic correlations between adult BCS and live weight (0.58-0.75) have been reported by Shackell et al. (2011), but there is limited publication of genetic correlations between BCS and other production traits, with no information about NZ Merinos. The aim of this study was to determine the heritability of BCS at each adult measurement throughout the production cycle of Merino ewes in New Zealand and estimate their phenotypic and genetic correlations to production traits.

4.3 Materials and methods

4.3.1 Animals

The data analysed were collected in the NZ Merino Central Progeny Trial (CPT) flock located in Omarama, Otago. The flock consisted of ewes born to 564 synchronised Merino ewes in 2013, 564 synchronised ewes in 2014 and the offspring from the 2013 born ewes that were born in 2015. The resulting 2,004 ewes from the three birth years (675 in 2013, 615 in 2014, 714 in 2015) were the offspring of 129 sires and were naturally mated first as two-year olds. The ewe traits recorded included; one-year-old (yearling) greasy fleece weight (GFW1), eye-muscle depth (EMD), fat depth; two-year-old greasy fleece weight (GFW2), fibre diameter (FD), coefficient of variation of fibre diameter, staple length, staple strength, pregnancy diagnosis (PD) and two-year-old body condition score (BCS). The BCS at weaning was only measured in the 2013-born and 2014-born cohorts. Fat depth and EMD measurements were taken as a yearling, as measurement at that age has previously been reported as having a greater heritability than the same measures at younger post-weaning ages (Mortimer et al. 2017).

Ewes were weighed and recorded for BCS four times as two-year olds, including immediately prior to mating in April (mating), at mid-pregnancy in June (scanning), just prior to lambing in. September (lambing), and at the time of weaning in December (weaning). The BCS were measured by Will Gibson on a 1-5 scale (Russel et al. 1969), with 0.25 increments. Additional data recorded included record date, birth year, sire, dam and rearing rank. Data were cleaned and traits were tested for normal distribution. BCS records that were not whole, or quarter scores between 0-5 were removed (n=169). Dam was determined by visual identification of lambs to their dams at birth for the 2013-born ewes and by DNA analysis for 2014-born ewes. The dams were not yet identified for the 2015 born ewes. Sire was determined by DNA analysis. From these data, animals which had at least a sire known were included.

4.3.2 Statistical analysis

Fixed effects were initially determined using mixed models in SAS version 9.4 (SAS Institute Inc., Cary, NC). Fixed effects fitted included; birthyear, lambing year, ewe RR, age, pregnancy diagnosis (PD) or contemporary group (birth year by RR by PD). Estimates of (co)variance components were obtained using the Julia for Whole-Genome Analyses Software (JWAS) package (Bezanson et al. 2017). A multivariate animal model was fitted that included the fixed effects of ewe birth year (2013, 2014 or 2015), record year (2015, 2016 or 2017) and the ewes own RR (1 or 2) for pre-mating BCS and mid-pregnancy BCS, with the addition of an effect for number of lambs carried (PD, 0, 1 or 2) for analysis of BCS before lambing and at weaning. Animal was fitted as a random effect. Least-squares mean and standard errors of the mean for each trait were obtained using the GLM procedure of SAS 9.4 (SAS Institute Inc., Cary NC, North Carolina).

4.4 Results

The mean BCS in two-year-old ewes were greatest at mating and declined to weaning (Table 4.1), the standard deviation of BCS at the different time points ranged from 0.27-0.31. Mean number of lambs born was 1.14 and the mean fibre diameter was 18.49 microns.

The 2013-born ewes had the greatest ($P<0.01$) BCS at mating and mid-pregnancy, but the lowest BCS before lambing and at weaning (Table 4.2). Fibre diameter was finest ($P<0.01$) in the 2013-born ewes and coarser ($P<0.01$) in 2014-born ewes. Staple length was greatest ($P<0.01$) in the 2013-born ewes and shortest in 2015-born ewes. Ewes that were reared as a multiple had slightly greater BCS at mating and weaning (Table 4.2).

Table 4.1. Summary statistics for traits of New Zealand Merino ewes including body condition score (BCS) at pre-mating, mid-pregnancy, pre-lambing and weaning, yearling greasy-fleece weight (Gfw1), ultrasound fat depth, eye-muscle depth (EMD), two-year-old greasy-fleece weight (Gfw2), pregnancy rate, fibre diameter, fibre-diameter coefficient of variation (CV), staple length and staple strength.

Trait	Animals	Sires	Mean	SD	Min	Max
Mating BCS	2,004	129	2.89	0.27	2.00	4.00
Mid pregnancy BCS	1,980	129	2.89	0.31	1.75	4.00
Pre-Lambing BCS	1,433	129	2.83	0.28	1.75	3.50
Weaning BCS	964	79	2.75	0.28	2.00	4.00
Fat depth (mm)	1,323	90	2.59	0.77	1.00	7.00
EMD (mm)	1,976	41	25.11	2.86	18	37
Gfw1 (kg)	1,978	130	3.20	0.86	1.6	5.1
Gfw2 (kg)	1,255	82	4.00	0.65	2.4	6.9
Pregnancy Rate	1,287	129	1.14	0.70	0	2
Fibre diameter (μm)	2,003	129	18.49	2.16	14.3	28.3
Fibre diameter CV (%)	2,003	129	17.78	2.44	11.9	27.5
Staple length (mm)	2,003	129	92.01	11.99	56	141
Staple strength (N/tex)	2,003	129	37.46	10.05	4	81

Table 4.2. Least-squares mean ± SEM of New Zealand Merino ewe body condition score (BCS) at pre-mating, mid-pregnancy, pre-lambing and weaning, yearling ultrasound measurements of fat depth and eye muscle depth, wool traits of yearling and two-year-old greasy fleece weight, fibre diameter, coefficient of variation (CV) of fibre diameter, staple length and staple strength

		Birth year				Ewe rearing rank	
Trait	n	2013	2014	2015	n	1	2+
BCS							
Mating	2,011	2.96±0.01[a]	2.90±0.01[b]	2.83±0.01[c]	962	2.91±0.01[b]	2.95±0.01[a]
Mid-Pregnancy	1,984	3.00±0.01[a]	2.78±0.01[c]	2.88±0.01[b]	961	2.84±0.01[b]	2.89±0.01[a]
Pre-lambing	1,437	2.72±0.02[c]	2.79±0.01[b]	2.92±0.01[a]	705	2.76±0.01	2.77±0.01
Weaning	965	2.66±0.01[b]	2.85±0.01[a]		718	2.80±0.02[a]	2.74±0.01[b]
Fat depth	1,980	2.02±0.02[c]	2.98±0.04[a]	2.76±0.03[b]	578	2.99±0.04	2.96±0.05
Eye muscle depth	1,980	24.2±0.1[c]	26.5±0.1[a]	25.0±0.1[b]	947	25.7±0.1	25.5±0.1
GFW1	1,982	3.61±0.02[a]	3.25±0.02[b]	3.06±0.02[c]	949	3.43±0.03[a]	3.23±0.02[b]
GFW2	1,255	3.61±0.02[b]	4.39±0.02[a]		943	4.15±0.03[a]	3.98±0.03[b]
Fibre diameter	2,007	17.7±0.08[c]	19.5±0.08[a]	18.4±0.08[b]	958	18.7±0.10	18.9±0.09
Fibre diameter CV	2,007	17.5±0.09[b]	16.9±0.09[c]	18.8±0.09[a]	958	16.9±0.1	17.2±0.1
Staple Length	2,007	95.5±0.5[a]	91.0±0.5[b]	89.6±0.4[c]	958	91.9±0.6[b]	94.0±0.5[a]
Staple Strength	2,007	37.2±0.3[b]	44.5±0.3[a]	31.7±0.3[c]	958	41.9±0.4	41.4±0.4

[a, b, c] within in rows means with different superscripts differ (P<0.05) between main effects within rows

Heritability for BCS ranged from 0.32 to 0.66 (Table 4.3) and was highest at the pre-mating measure. The heritability for ultrasound measurements of fat depth and EMD ranged from 0.52 to 0.64 and wool-trait heritability ranged from 0.61 to 0.86 with fibre diameter having the highest heritability.

The genetic correlations between BCS measurements ranged from 0.39-0.83, while the phenotypic correlations ranged from 0.22-0.45. Genetic correlations between BCS and fat depth ranged from 0.56-0.83 and between BCS and EMD ranged from 0.54-0.87 while the phenotypic correlations ranged from 0.20-0.47 and from 0.24-0.53 respectively. The genetic correlations between BCS and two-tooth greasy fleece weight (-0.08-0.24) and fibre diameter (0.38-0.51) were unfavourable. The genetic correlations between BCS and staple length (0.10-0.27) and staple strength (0.03-0.09), fibre diameter CV (-0.21-0.17) and yearling greasy fleece weight (0.09-0.19) were favourable.

Table 4.3. Estimates of heritabilities (diagonal), phenotypic (above diagonal) and genetic (below diagonal) correlations ± SEM for body condition score (BCS) prior to mating, mid pregnancy, pre-lambing and weaning, ultrasound scanning measurements of fat depth and eye muscle depth (EMD) as a one-year-old, greasy fleece weight as a one- (GFW1) and two-year-old (GFW2), fibre diameter, coefficient of variation (CV) of fibre diameter, staple length and staple strength of New Zealand Merino ewes.

Trait	BCS pre-mating	BCS mid-pregnancy	BCS pre-lambing	BCS weaning	Fat Depth	EMD	GFW1	GFW2	Fibre diameter	Fibre diameter CV	Staple length	Staple strength
BCS pre-mating	**0.66±0.01**	0.42±0.01	0.43±0.01	0.34±0.01	0.47±0.01	0.53±0.01	0.52±0.01	0.46±0.01	0.30±0.01	-0.09±0.01	0.20±0.01	0.05±0.01
BCS mid-pregnancy	0.71±0.01	**0.39±0.01**	0.45±0.01	0.22±0.01	0.20±0.01	0.24±0.01	0.20±0.01	0.24±0.01	0.20±0.01	-0.09±0.01	0.09±0.01	0.02±0.01
BCS pre-lambing	0.83±0.01	0.79±0.01	**0.46±0.01**	0.34±0.01	0.34±0.01	0.40±0.01	0.05±0.01	-0.09±0.01	0.27±0.01	-0.09±0.01	0.11±0.01	0.03±0.01
BCS weaning	0.71±0.01	0.39±0.01	0.72±0.01	**0.32±0.01**	0.28±0.01	0.30±0.01	0.03±0.01	-0.10±0.01	0.17±0.01	-0.03±0.01	0.07±0.01	0.02±0.01
Fat depth	0.83±0.01	0.56±0.01	0.80±0.01	0.67±0.01	**0.52±0.01**	0.71±0.06	-0.09±0.01	0.09±0.01	0.31±0.01	-0.08±0.01	0.16±0.01	0.07±0.01
EMD	0.87±0.01	0.54±0.01	0.80±0.01	0.72±0.01	0.88±0.05	**0.64±0.01**	0.05±0.01	0.10±0.01	0.27±0.01	-0.12±0.01	0.19±0.01	0.04±0.01
GFW 1	0.19±0.01	0.10±0.01	0.19±0.01	0.09±0.01	0.49±0.01	0.53±0.01	**0.65±0.01**	0.69±0.01	0.19±0.01	0.06±0.01	0.17±0.01	0.06±0.01
GFW 2	-0.15±0.01	-0.08±0.01	-0.18±0.01	-0.24±0.01	-0.01±0.01	-0.05±0.01	0.76±0.01	**0.52±0.01**	0.14±0.01	0.11±0.01	0.15±0.01	0.03±0.01
Fibre diameter	0.51±0.01	0.38±0.01	0.46±0.01	0.41±0.01	0.46±0.01	0.38±0.01	0.21±0.01	0.07±0.01	**0.86±0.01**	0.20±0.01	0.40±0.01	0.28±0.01
Fibre diameter CV	-0.07±0.01	-0.21±0.01	-0.09±0.01	0.17±0.01	-0.11±0.01	-0.18±0.01	0.04±0.01	0.11±0.01	0.16±0.01	**0.61±0.01**	0.04±0.01	-0.26±0.01
Staple length	0.27±0.01	0.17±0.01	0.17±0.01	0.10±0.01	0.21±0.01	0.26±0.01	0.19±0.01	0.09±0.01	0.06±0.01	-0.26±0.01	**0.73±0.01**	0.18±0.01
Staple strength	0.03±0.01	0.05±0.01	0.04±0.01	0.09±0.01	0.06±0.01	0.03±0.01	0.04±0.01	0.04±0.01	0.02±0.01	-0.44±0.01	-0.02±0.01	**0.71±0.01**

4.5 Discussion

The mean BCS in the current study was consistent with the mean BCS reported by Shackell et al. (2011) in New Zealand crossbred ewes, but was lower than that reported by Walkom et al. (2014b) and Walkom & Brown (2017) for Australian Merino and crossbred ewes. The BCS of Merino-cross ewes reported by Walkom & Brown (2017) showed a decline from mating through to weaning, which was consistent with the current study. This decline in BCS is to be expected, as ewes use their body reserves to provide energy for pregnancy and lactation. The mean fat depth, EMD, fibre diameter, fibre diameter CV, staple length and staple strength in the current study were consistent with those reported by Walkom and Brown (2017). Yearling greasy fleece weight in the current study was slightly greater than that reported by Walkom and Brown (2017).

The standard deviation for BCS ranged from 0.23-0.26 in the current study and was lower than the standard deviation (0.53-0.58) reported by Walkom & Brown (2017), indicating there was less variation in the data of the current study. The mean fat depth was 2.59 mm which was consistent with other studies in Merino sheep (Swan et al. 2016; Mortimer et al. 2017), whilst the standard deviation of 0.77 was lower than reported in these studies. It is consistent, through all the traits in the current study, that the variation in the current study was less than the variation in the results presented by Walkom & Brown (2017) which included crossbred animals and measured BCS on 1-5 scale with 0.5 increments.

Heritability for BCS in the current study ranged from 0.32-0.66 which is greater than published heritabilities for Australian Merino ewes of 0.08-0.11 reported by Walkom et al. (2014b) and 0.11 reported by Brown et al. (2017). Heritabilities of BCS reported in other breeds ranged from 0.15 to 0.30 (Shackell et al. 2011; Walkom et al., 2016; Walkom & Brown, 2017) which were also lower than the heritabilities reported in the current study. Similarly, the EMD heritability in the current study was greater than reported heritabilities of 0.24 (Safari et al. 2005) and 0.22 (Brown et al. 2017). Eye-muscle width measurements were not considered in this study, which is supported by Safari et al. (2005) who reported a low heritability for eye-muscle width of 0.06, representing the poor accuracy of this ultrasound measurement. Fat-depth heritability estimates in the current study were higher than those reported in previous studies of 0.19-0.26 (Safari et al. 2005; Swan et al. 2016; Mortimer et al. 2017). Yearling greasy fleece weight heritability was 0.65 ± 0.01, which is greater than other reported yearling greasy fleece weight of 0.32-0.57 (Swan et al. 2016; Mortimer et al. 2017). The fibre-diameter heritability of 0.86 in the current study is slightly higher than those reported by Mortimer et al. (2017), whereas the fibre diameter CV heritability in the current study was much higher than 0.34 reported by Mortimer et al. (2017) and slightly higher than the 0.50 reported by Swan et al. (2016). Staple strength and staple length heritabilities were 0.73 and 0.71 in the current study, which were greater than those reported by Swan et al. (2016) of 0.35 and 0.66 respectively.

The higher heritability estimates in the current study compared to those in published literature for Merino ewes could be due to the low variation in the data, which results in low estimates of phenotypic variance. The phenotypic variance is further underestimated due to fixed effects that were not recorded, but were present in the flock, therefore could not be adjusted for, such as birth rank or age of dam. Another issue overestimating the heritability estimates are the sire and dam groups being unique to each year cohort, resulting in the year effect confounding with sire group inflating the genetic variance and the heritability estimates. The dams were unique to each year cohort and the dams were not pedigree recorded the lambs were, therefore they were missing key information to link the pedigree across cohort year. Sires were unique to each year.

The pre-mating, mid-pregnancy, pre-lambing and weaning BCS were moderately phenotypically correlated but were highly genetically correlated and also highly genetically correlated to fat depth and EMD (Table 4.3),. This is consistent with the findings of Walkom & Brown (2017) and Brown and Swan (2014), confirming that a single record of BCS each year is sufficient to assess the genetic potential for BCS. The BCS were low-to-moderately phenotypically correlated and moderately genetically correlated to the wool traits of fibre diameter, yearling greasy-fleece weight and staple length which is in agreement with the phenotypic correlations reported by Walkom and Brown (2017) for yearling fibre diameter and staple length.

The pre-mating BCS consistently had the highest genetic correlation with all traits, which is in agreement with the correlations reported by Walkom and Brown (2017). This is likely to be able to the ewes are not being affected by pregnancy or lactation before mating. Heritability indicates this is the BCS measurement under greatest genetic influence.

The heritabilities reported in the current study indicate that a moderate to high rate of genetic gain could be achieved for BCS and a high rate of genetic gain could be achieved for Merino lamb growth and wool traits. The heritability estimates and genetic correlations of the current study would be strengthened by having records of the contemporary groups of birth rearing rank and age of dam recorded for the animals. The current pedigree file included only recorded data of the ewes with recorded sire whereas, if there were also data recorded for dams, it would have improved the linkage across years.

4.6 Conclusions

Mating appears to be the best time to record BCS for genetic selection, as it had the greatest heritability estimate and the greatest genetic correlations with ultrasound measurements of fat depth and eye-muscle depth and all wool traits except fibre diameter coefficient of variation and greasy fleece weight. In conclusion, BCS could be useful to be recorded by more breeders to include in the genetic evaluation system to improve accuracy of selection for wool traits in NZ Merino ewes. More high-quality data with linkage across sires and dams are required for BCS to confirm these associations.

5 Genetic parameters for body condition score in New Zealand dual-purpose sheep

5.1 Abstract

This chapter adds to the previous one on Merino ewes, focusing on dual-purpose ewes and investigating genetic and phenotypic correlations between BCS and production in this population of ewes. Pedigree-recorded dual-purpose ewes (n=9,585) were weighed and condition scored at mating and weaning as a two- and three- year old. Birth year of the ewes ranged from 2008 to 2016. Ewes were part of a nucleus breeding flock managed under commercial conditions. This chapter evaluated BCS as four individual traits including mating BCS and weaning BCS as a two- and three- year-old ewe. Heritability of body condition score (BCS) at mating and weaning as a two-year-old ewe were 0.16 and 0.19, respectively and as a three-year old were 0.22 and 0.17, respectively indicating that a moderate genetic change could be achieved if BCS selection is made. Genetic correlations between the BCS measurements across years were moderate to high (0.49-0.89), that shows BCS is likely controlled by similar genes across the life of the ewe. There was a negative genetic correlation between mating BCS and NLS both as two- and three-year olds (-0.18 and -0.23) indicating that selecting for increased BCS will reduce reproductive performance. However, the phenotypic correlation was negligible indicating that in this population of sheep, greater BCS ewes are no more productive than the lower BCS ewes.

5.2 Introduction

Greater body condition score (BCS) of the ewe is a key driver of pregnancy status, number of lambs weaned per ewe, lamb weaning weight and total litter weaning weight (Chapter 3, Gunn et al. 1991a; Gunn et al. 1991b; Molina et al. 1991; Kenyon et al. 2012; Mathias-Davis et al. 2013; Kenyon et al. 2014). In Chapter 3, a BCS above 3.5 resulted in lower total litter weaning weight than a BCS below 3.5. It has been previously reported that both above- and below-target BCS resulted in lower ovulation rates, conception rates, embryo mortality, number of lambs weaned and lamb weaning weight (Gunn et al. 1991b; Abdel-Mageed 2009; Kenyon et al. 2014; Sae-Lim et al. 2018). Therefore, it is favourable to have the greatest number of ewes maintain a phenotypic BCS between 3.0 and 3.5 at mating.

There are numerous phenotypic traits recorded in the Sheep Improvement Limited (SIL) database for terminal, maternal and mid-micron wool breed types. Maternal traits for dual-purpose ewes include but not limited to: reproduction (based on number of lambs born), lamb survival to weaning, lamb growth (weaning weight and carcass weight), live weight (adult size), wool weight and BCS (Sheep Improvement Limited 2017). Live weight has a negative relative economic value resulting in a slowed increase in ewe liveweight (Sheep Improvement Limited 2017). Selection for a low ewe live weight could be indirectly selecting for low BCS or limiting genetic BCS progress, due to the high genetic correlation between live weight and BCS (Shackell et al. 2011; Kenyon et al. 2014; Morel et al. 2016). Heritability estimates of BCS in New Zealand dual-purpose ewes have varied between 0.16 to 0.30 indicating a moderate rate of genetic change could be achieved if selection for greater BCS is made (Everett-Hincks and Cullen 2009; Shackell et al. 2011).

The relationships between BCS and key production traits must also be considered to evaluate correlated genetic responses for other traits under different selection strategies. There have been few studies that have reported the genetic correlations between BCS and production traits in sheep. Everett-Hincks and Cullen (2009) reported that the genetic correlations between ewe BCS and lamb survival were high, but the genetic correlations between ewe BCS and lamb weaning weight were low. In contrast, Walkom and Brown (2017) using data from 13,700 Australian crossbred ewes reported that the genetic correlations between ewe BCS and lamb growth traits (weaning weight and post-weaning weight) were high (0.44-0.71). The genetic correlation between BCS and production in NZ dual-purpose sheep must be considered to determine the effect of BCS selection on other traits.

To date, there is no published data to the authors knowledge on the genetic correlations, in New Zealand dual-purpose ewes, between BCS across a number of ages and the production traits, including number of lambs born (NLB), number of lambs weaned (NLW) and lamb weaning weight (avWWT). The aim of this chapter was to determine the heritability, phenotypic and genetic correlations between ewe BCS, live weight and production traits in dual-purpose ewes.

5.3 Materials and Methods

5.1.1 Data background

Data was retrieved from four Focus Genetics nucleus breeding flocks, as described in Table 5.1, for the period that the BCS measurements were taken of 2008 to 2017. Three of the four flocks were located in the North Island of New Zealand, while the other flock was in the South Island (Figure 5.1). Chapter 3 used a subset of this data, using only the Freestone flock.

Table 5.1. Description of Focus Genetics farms (flock) including the name, location, size (ha), sheep breed and number of ewes in the nucleus flock.

Farm name	Location (nearest town)	Size (effective ha)	Breed	Number of ewes in the Nucleus flock
Goudies	Reporoa	1,750	Romney	3,000
Freestone	Te Anau	630	Romney	1,200
Pohuetai	Dannevirke	1,970	Highlander	1,180
Waipuna	Whanganui	2,250	Highlander	700

Two of the flocks were comprised of the Romney breed and the other two were Highlander. The Highlander is a self-replacing stabilized maternal composite breed which was originally created from crossing the Romney (0.50), Texel (0.25) and Finn (0.25) breeds.

Ewes were first presented for mating at 8-months of age unless feed supply was limited, in which case ewes were mated first at 20-months of age (5/44 flock-birthyear groups). Ewes were managed under NZ commercial farming conditions. Ewes were culled if they were diagnosed as not pregnant at pregnancy scanning, were assisted at lambing or did not wean a lamb. Ewes were also culled based on their teeth, udder, feet, age or selection index. Along with the nucleus flocks, commercial cattle and deer were farmed at Goudies, recorded deer and commercial sheep and cattle were farmed at Freestone and commercial sheep and cattle were farmed at Waipuna and Pohuetai.

5.1.2 Animals

The dataset included 53,620 ewe lambs weighed at weaning at approximately three-months of age between 2008 to 2016. Of these ewe lambs 24,272 went on to lamb at one-year of age, 6,772 lambed for the first time at two-years of age. Ewes had both their sire and dam identified based on DNA parentage. The age of the ewe's dam (AOD) ranged from one to eight years.

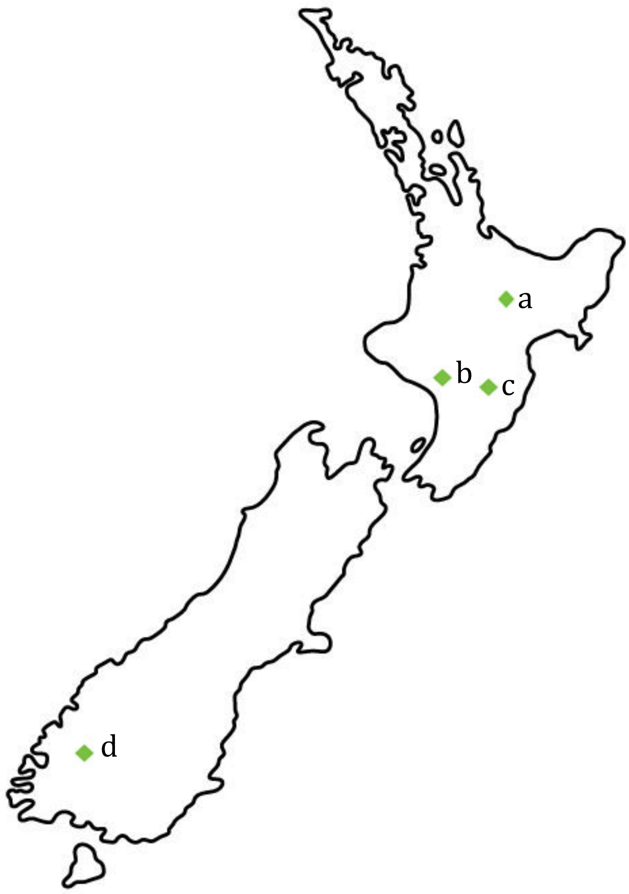

Figure 5.1. Map of New Zealand with the Focus Genetic farm sites a) Goudies, b) Waipuna, c) Pohuetai, d) Freestone.

As the majority of these ewes were intended to be first bred at 8 months of age, one of the traits considered in selection of flock replacements was their individual post-weaning live weight. Post-weaning live weight is strongly phenotypically related to weaning weight (WWT), therefore, ewe lambs selected to be retained as replacements were likely to be those with the greatest live weights at weaning. All ewe lambs that had a WWT record in the dataset have been included in the analysis, not just those that were selected as replacements, to ensure that the selection pressure was accounted for.

5.1.3 Measurements

Ewe BCS was recorded between 2011-2017 for up to three-years of age on each ewe, measured twice annually at mating and weaning, on a 1-5 scale (Jefferies 1961) with 0.5 increments. The two annual BCS measurements were made prior to mating in March/April (mating) recorded at 18- and 30-months of age, and at weaning in December (weaning) recorded at 27- and 39-months of age. Ewe liveweight was recorded at 3- (WWT), 18- and 30-months of age. The number of lambs scanned (NLS) was the number of fetuses detected at pregnancy diagnosis (approximately day 75 of pregnancy). This was determined using ultrasound scanning (as per SIL database procedure) and ranged from one to six. The NLS was recorded at 9-, 21- and 34-months of age. The number of lambs born was not recorded due to no shepherding at lambing. The NLW was recorded for each ewe at 15-, 27- and 39-months of age as number of lambs present at weaning based on DNA parentage and ranged from one to six. One-year-old ewe records of NLS and NLW were not included in the analysis.

5.1.4 Data editing

The Focus Genetics data were cleaned and traits were tested for normal distribution. BCS records that were not whole or half scores between 0-5 were removed (0.003%). Ewes that had rearing rank values that were negative or zero were removed (4.2%). One-year-old records were excluded (n=2,315) because they did not have mating BCS measurements and five-year-old records were excluded (n=364) due to the small number of ewes left at that age within each birthyear group.

The ewe birth rank and rearing rank of 3, 4, 5 and 6 were classed as 3+. Ewe birth-rearing rank (BR_RR) was classified according to the following combinations of her dam's NLB and NLW; scanned single-bearing and weaned single (1_1), scanned twin-bearing and weaned twins (2_2), scanned twin-bearing and weaned one lamb (2_1), scanned triplet-bearing and weaned triplets (3_3), scanned triplet-bearing and weaned twins (3_2) or single (3_1). If no NLB data were entered for an animal, the pregnancy ultrasound scanning data (NLS) were used as a proxy for NLB. Industry estimates indicate a 98% agreement between NLS and NLB (Farmer and Davis 1999).

When the NLS and NLW subsequently produced by the ewe were considered, ewes with more than 3 lambs at pregnancy diagnosis (NLS) or weaning (NLW) were removed from the dataset for that lambing year (mating to weaning, n=686, 1.3%). The AOD was classified into three age groups (1, 2 or 3+). Age of the ewe at first lambing (AFL) was defined based on records as to whether the ewe had a lamb recorded at lambing as a one-year or a two-year old.

5.1.5 Statistical Analysis

Descriptive statistics of mean, standard deviation, minimum and maximum for ewe weaning weight (WWT), BCS at weaning as a one- (BCSwean1), two- (BCSwean2) and three-year-old (BCSwean3), live weight at mating as a two- (LWmate2), and three-year-old (LWmate3), BCS at mating as a two- (BCSmate2) and three-year-old (BCSmate3), number of lambs scanned at pregnancy diagnosis as a two- (NLS2) and three-year-old (NLS3), number of lambs weaned as a two- (NLW2) and three-year-old (NLW3) were obtained using SAS version 9.4 (SAS Institute Inc., Cary, NC).

Fixed effects were initially determined using SAS version 9.4 (SAS Institute Inc., Cary, NC). Fixed effects fitted included; lambing year, parity, flock, BR_RR, age, AFL, AOD and NLS_NLW or contemporary group (lambing year by flock by AFL). These effects were tested and discarded from the final model if not significant. To assess the significance of maternal, permanent environment and animal random effects, these were fitted in univariate models for each trait using ASReml (Gilmour et al. 2009). All random effects were used in the final model.

Weaning weight, BCSwean1, BCSwean2, BCSwean3, LWmate2, LWmate3, BCSmate2, BCSmate3, NLS2, NLS3, NLW2 and NLW3 were attempted to be estimated using a multivariate animal model, however, because of the long computing time, the multivariate animal model was run with three traits at a time. A series of tri-variate animal models (n=55) were fitted in ASReml (Gilmour et al. 2009). WWT was fitted as a trait every tri-variate model with two other traits; ewe BCS at mating, ewe mating liveweight, BCS at weaning, NLS and NLW at each age. Contemporary group was defined as ewes lambing in the same year, flock and AFL. The animal model for ewe BCS at mating, ewe mating liveweight, NLS and NLW at each age included the fixed effects of contemporary group, AOD, ewe birth-rearing rank, and the random effect of animal. For the analysis of BCS at weaning the model included the fixed effects of contemporary group, AOD, ewe birth-rearing rank, the combination of NLS and NLW and the random effect of animal. For WWT the model included the fixed effects of contemporary group, AOD, ewe birth-rearing rank, random effect of animal and the random effect of dam.

In matrix notation, the tri-variate models can be represented as:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} X_1 & 0 & 0 \\ 0 & X_2 & 0 \\ 0 & 0 & X_3 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} + \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_3 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} + \begin{bmatrix} W_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} m_1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} P_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} c_1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

Where y_1 are the vectors of phenotypic WWT, y_2 and y_3 are the vectors of phenotypic measures for one of the other two traits; BCSwean1, BCSwean2, BCSwean3, LWmate2, LWmate3, BCSmate2, BCSmate3, NLS2, NLS3, NLW2 and NLW3; X_1, X_2 and X_3, and Z_1, Z_2 and Z_3 are design matrices relating the fixed and additive genetic effects to the phenotypes, respectively; W_1 is an incidence matrix relating the WWT records to the maternal effects on the animal, P_1 is an incidence matrix relating the WWT records to the permanent environment effects on the animal, b_1, b_2 and b_3 are the vectors of fixed effects of contemporary group, AOD, ewe birth-rearing rank and the combination of NLS and NLW; a_1, a_2 and a_3 are the vectors of random effects of animal for each trait; m_1 is the vector of maternal effects for ewe for WWT; c_1 is the vector of random effects for ewe for WWT; and e_1, e_2 and e_3 are vectors of residual errors not accounted for by the fixed and animal effects. The distributional properties of the elements in the model with E and V indicating the expectation and variance were as follows:

$$E\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ a_1 \\ a_2 \\ a_3 \\ m_1 \\ c_1 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} X_1 b_1 \\ X_2 b_2 \\ X_3 b_3 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

And

$$V\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ m_1 \\ c_1 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} A\sigma^2_{a1} & A\sigma^2_{a12} & A\sigma^2_{a13} & A\sigma^2_{a1m1} & 0 & 0 & 0 & 0 \\ A\sigma^2_{a12} & A\sigma^2_{a2} & A\sigma^2_{a23} & A\sigma^2_{a2m1} & 0 & 0 & 0 & 0 \\ A\sigma^2_{a13} & A\sigma^2_{a23} & A\sigma^2_{a3} & A\sigma^2_{a3m1} & 0 & 0 & 0 & 0 \\ A\sigma^2_{a1m1} & A\sigma^2_{a2m1} & A\sigma^2_{a3m1} & A\sigma^2_{m1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_1\sigma^2_{c1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_2\sigma^2_{e1} & I_2\sigma^2_{e12} & I_2\sigma^2_{e13} \\ 0 & 0 & 0 & 0 & 0 & I_2\sigma^2_{e12} & I_2\sigma^2_{e2} & I_2\sigma^2_{e23} \\ 0 & 0 & 0 & 0 & 0 & I_2\sigma^2_{e13} & I_2\sigma^2_{e23} & I_2\sigma^2_{e3} \end{bmatrix}$$

Where A is the numerator relationship matrix of order 140,564, the total number of animals in the pedigree file; σ^2_{a1}, σ^2_{a2}, σ^2_{a3}, σ_{a12}, σ_{a13} and σ_{a23} are the animal (co)variance components for the traits under consideration; σ_{a1m1}, σ_{a2m1} and σ_{a3m1} are the animal and maternal covariance components ; I_1 is an identity matrix of size 53,654, the number of ewes with WWT records; σ^2_{c1} is the ewe permanent environmental (co)variance component for traits being considered; I_2 is an identity matrix of size 53,654, the number of records; σ^2_{e1}, σ^2_{e2}, σ^2_{e3}, σ_{e12}, σ_{e13} and σ_{e23} are the residual (co)variance components for the traits. Estimates of (co)variance components were obtained using the Restricted Maximal Likelihood procedure in ASReml package (Gilmour et al. 2009) of VSN International Ltd.

Heritabilities (h^2) for BCS, live weight, NLS and NLW were obtained as:

$$h^2 = \frac{\sigma_a{}^2}{\sigma_T{}^2}$$

where the total phenotypic variance was calculated as:

$$\sigma_T^2 = \sigma_a^2 + \sigma_e^2$$

Where σ_T^2 is the total phenotypic variance, σ_a^2 is the additive animal variance and σ_e^2 is the residual variance.

The total (h_T^2), direct (h_d^2), and maternal (h_m^2), heritabilities for WWT were calculated as:

$$h_T^2 = \frac{\sigma_{a1}^2 + 1.5\sigma_{a1m1} + 0.5\sigma_{m1}^2}{\sigma_{p1}^2} \qquad h_d^2 = \frac{\sigma_{a1}^2}{\sigma_{p1}^2} \qquad h_m^2 = \frac{\sigma_{m1}^2}{\sigma_{p1}^2}$$

where

$$\sigma_{p1}^2 = (\sigma_{a1}^2 + \sigma_{m1}^2 + \sigma_{c1}^2 + \sigma_{a1m1} + \sigma_e^2)$$

where σ_{p1}^2 is the total phenotypic variance for WWT (Willham 1963).

Genetic correlations (r_g) were estimated as:

$$r_g = \frac{\sigma_{aij}}{\sigma_{ai}\sigma_{aj}}$$

where:

σ_{aij} = genetic covariance between trait i and trait j;

σ_{ai} = genetic covariance between trait i, equivalent to $\sqrt{\sigma_{ai}^2}$;

σ_{aj} = genetic covariance between trait j, equivalent to $\sqrt{\sigma_{aj}^2}$;

and phenotypic correlations (r_p) as:

$$r_p = \frac{\sigma_{pij}}{\sigma_{pi}\sigma_{pj}}$$

where:

σ_{pij} = phenotypic covariance between trait 1 and trait 2, equivalent to $\sigma_{aij} + \sigma_{cij} + \sigma_{eij}$;

σ_{pi} = phenotypic covariance between trait 1, equivalent to $\sqrt{\sigma^2_{ai} + \sigma^2_{ci} + \sigma^2_{ei}}$;

σ_{pj} = phenotypic covariance between trait 1, equivalent to $\sqrt{\sigma^2_{aj} + \sigma^2_{cj} + \sigma^2_{ej}}$;

5.4 Results

Mean BCS was greatest at BCSmate2 (3.55) and lowest at BCSwean1 (2.95, Table 5.2). The standard deviation for BCS was greatest at BCSwean1 (0.67) and lowest at BCSmate2 (0.55, Table 5.2). Mean live weight was greater and mean BCS lower at mating as a three-year-old compared with two-year-old (Table 5.2).

Body condition score was moderately heritable (0.16-0.22; Table 5.3). LWmate2 and LWmate3 were highly heritable (0.40-0.45) and NLS and NLW were lowly heritable (0.02-0.08). The genetic variance for the BCS measurements varied from 0.03 to 0.06 (Table 5.3).

Table 5.2. Number of animals (n), mean, standard deviation (SD), minimum (min) and maximum (max) for weaning weight (WWT), BCS at weaning as a one- (BCSwean1), two- (BCSwean2) or three-year-old (BCSwean3), live weight at mating as a two- (LWmate2), and three-year-old (LWmate3), BCS at mating as a two- (BCSmate2) and three-year-old (BCSmate3), number of lambs scanned at pregnancy diagnosis as a two- (NLS2) and three-year-old (NLS3), number of lambs weaned as a two- (NLW2) and three-year-old (NLW3) of New Zealand Romney and Highlander ewes.

Trait	n	Mean	SD	min	max
WWT (kg)	53,620	26.69	5.43	6.6	53.0
BCSwean1	3,247	2.95	0.67	1.0	5.0
BCSmate2	9,585	3.55	0.55	1.5	5.0
BCSwean2	5,408	3.20	0.59	1.0	5.0
BCSmate3	6,575	3.35	0.56	1.5	5.0
BCSwean3	3,835	3.12	0.62	1.0	5.0
LWmate2 (kg)	17,280	59.56	8.96	34.5	97.5
LWmate3 (kg)	11,141	64.09	8.34	39.0	99.5
NLS 2	20,773	1.87	0.76	0.0	3.0
NLS 3	12,809	2.05	0.72	0.0	3.0
NLW 2	15,276	1.54	0.74	0.0	3.0
NLW 3	9,979	1.69	0.76	0.0	3.0

Direct heritability for weaning weight was 0.30 and maternal heritability for weaning weight was 0.35, however, the total heritability for WWT was 0.18 (Table 5.4). The variance of the maternal effect, permanent environment effect and the covariance between the two components, were 1.47 ± 0.21, 2.71 ± 0.12 and -1.05 ± 0.10 respectively.

The greatest genetic correlations with direct weaning weight (WWT_d, 0.33—0.41) and maternal weaning weight (WWT_m, 0.36—-0.43) were between LWmate2 and LWmate3 (Table 5.5). Genetic correlations between WWT_d and BCS were negative to low (-0.01—0.10), while the genetic correlations between WWT_m and BCS were negative to moderate (-0.10—0.34).

Genetic correlations between the same trait measured at different times are presented in Table 5.5. The genetic correlation between the same measurements recorded at different periods were high (0.49-0.89). This was true for BCSmate, BCSwean, LWmate, NLS and NLW. Genetic correlations between BCS and NLS ranged from -0.30 to 0.20 and the genetic correlations between BCS and NLW ranged from -0.49 to 0.25.

BCS measured at different times were moderately phenotypically correlated (0.17-0.51). Live weight as a two-year-old was highly phenotypically correlated with three-year-old live weight (0.69). The phenotypic correlation between BCS and NLS was low (-0.09-0.10).

Table 5.3. Estimates of genetic ($\hat{\sigma}_g^2$) and residual ($\hat{\sigma}_e^2$) variances and heritability (h^2) for BCS at weaning as a one- (BCSwean1), two- (BCSwean2) and three-year-old (BCSwean3), BCS at mating as a two- (BCSmate2) and three-year-old (BCSmate3), live weight at mating as a two- (LWmate2) and three-year-old (LWmate3), number of lambs scanned at pregnancy diagnosis as a two- (NLS2) and three-year-old (NLS3), number of lambs weaned as a two- (NLW2) and three-year-old (NLW3) of New Zealand Romney and Highlander ewes. Values are estimate ± SEM.

Trait	$\hat{\sigma}_g^2$	$\hat{\sigma}_e^2$	$\hat{h}^2$
BCSwean1	0.06±0.01	0.26±0.01	0.20±0.03
BCSmate2	0.03±0.01	0.16±0.01	0.16±0.02
BCSwean2	0.05±0.01	0.22±0.01	0.19±0.03
BCSmate3	0.05±0.01	0.15±0.01	0.22±0.01
BCSwean3	0.05±0.01	0.25±0.01	0.17±0.01
LWmate2	14.03±0.71	21.31±0.52	0.40±0.02
LWmate3	18.58±1.05	22.30±0.75	0.45±0.02
NLS2	0.04±0.01	0.49±0.01	0.08±0.01
NLS 3	0.04±0.01	0.46±0.01	0.08±0.01
NLW 2	0.01±0.01	0.52±0.01	0.02±0.01
NLW 3	0.01±0.01	0.56±0.01	0.02±0.02

Table 5.4. Estimates of additive ($\hat{\sigma}_a^2$), maternal ($\hat{\sigma}_m^2$), permanent environment ($\hat{\sigma}_{pe}^2$) and residual ($\hat{\sigma}_e^2$) variances, covariance between the additive and maternal effects ($\hat{\sigma}_{am}$) and direct ($\hat{h}_d^2$), maternal ($\hat{h}_m^2$) and total ($\hat{h}_t^2$) heritability for weaning weight (WWT) of New Zealand Romney and Highlander ewes. Values are estimate ± SEM.

	WWT
$\hat{\sigma}_a^2$	4.77±0.35
$\hat{\sigma}_m^2$	1.47±0.21
$\hat{\sigma}_{pe}^2$	2.71±0.12
$\hat{\sigma}_e^2$	11.16±0.21
$\hat{\sigma}_{am}$	-1.05±0.10
$\hat{h}_d^2$	0.30±0.02
$\hat{h}_m^2$	0.35±0.01
$\hat{h}_t^2$	0.18±0.01

Table 5.5. Genetic (below diagonal) and phenotypic (above diagonal) correlations between the direct effect of weaning weight (WWT_d), maternal effect of weaning weight (WWT_m), total effect of weaning weight (WWT_t), BCS at weaning as a one- (BCSwean1), two- (BCSwean2) and three-year-old (BCSwean3), live weight at mating as a two- (LWmate2) and three-year-old (LWmate3), BCS at mating as a two- (BCSmate2) and three-year-old (BCSmate3), number of lambs scanned at pregnancy diagnosis as a two- (NLS2) and three-year-old (NLS3), number of lambs weaned as a two- (NLW2) and three-year-old (NLW3) of New Zealand Romney and Highlander ewes.

	WWT_d	WWT_m	BCSwean1	BCSmate2	BCSwean2	BCSmate3	BCSwean3	LWmate2	LWmate3	NLS2	NLS3	NLW2	NLW3
WWT_d			0.13±0.02	0.07±0.01	0.05±0.01	0.02±0.01	0.02±0.01	0.39±0.01	0.35±0.01	0.05±0.01	-0.01±0.01	0±0.01	-0.04±0.01
WWT_m	-0.50±0.04												
BCSwean1	0.09±0.11	-0.06±0.12		0.51±0.01	0.17±0.03	0.17±0.03	0.25±0.03	0.51±0.01	0.21±0.03	0.09±0.02	0.03±0.03	0.07±0.02	0.02±0.03
BCSmate2	0.09±0.08	0.25±0.08	0.79±0.07		0.23±0.01	0.28±0.01	0.19±0.02	0.51±0.01	0.25±0.01	0.04±0.01	0.01±0.01	0.01±0.01	0.03±0.02
BCSwean2	0.11±0.09	0.13±0.09	0.87±0.11	0.77±0.07		0.49±0.01	0.39±0.02	0.24±0.01	0.49±0.01	-0.09±0.02	0.09±0.02	-0.37±0.02	0.03±0.02
BCSmate3	0.09±0.08	0.36±0.07	0.72±0.11	0.89±0.05	0.89±0.04		0.30±0.02	0.24±0.01	0.55±0.01	-0.08±0.01	0.05±0.01	-0.25±0.01	0.02±0.01
BCSwean3	0.01±0.10	0.11±0.10	0.56±0.14	0.49±0.11	0.79±0.09	0.67±0.08		0.19±0.02	0.19±0.02	0.01±0.02	0.10±0.02	-0.04±0.02	-0.36±0.02
LWmate2	0.46±0.04	0.35±0.04	0.41±0.07	0.53±0.05	0.43±0.06	0.51±0.05	0.23±0.08		0.69±0.01	0.11±0.01	0.03±0.01	0.03±0.01	-0.01±0.01
LWmate3	0.40±0.05	0.36±0.05	0.23±0.10	0.54±0.06	0.48±0.06	0.57±0.04	0.23±0.08	0.95±0.01		0.01±0.01	0.08±0.01	-0.21±0.01	0.01±0.01
NLS2	0.05±0.07	-0.12±0.07	0.07±0.14	-0.18±0.09	-0.10±0.10	-0.15±0.09	-0.09±0.11	0.08±0.06	-0.06±0.06		0.14±0.01	0.62±0.01	0.07±0.01
NLS3	-0.11±0.09	-0.03±0.09	-0.02±0.18	-0.21±0.12	0.01±0.12	-0.23±0.11	0.21±0.13	-0.15±0.07	-0.08±0.08	0.84±0.07		0.04±0.01	0.61±0.01
NLW2	-0.17±0.13	0.04±0.14	-0.18±0.24	-0.20±0.17	-0.49±0.17	-0.14±0.16	-0.30±0.19	-0.24±0.12	-0.16±0.12	0.76±0.07	0.54±0.15		0.10±0.01
NLW3	-0.33±0.19	0.06±0.19	-0.11±0.35	-0.09±0.25	0.01±0.25	-0.23±0.24	0.23±0.31	-0.71±0.22	-0.50±0.20	0.69±0.21	0.80±0.10	0.83±0.24	

5.5 Discussion

The current chapter examines traits important to lamb production in a population of dual-purpose ewes. This study was the first in New Zealand that focused on BCS and considered the phenotypic and genetic correlations between BCS measurements across multiple ages.

5.1.6 Heritabilities

The heritabilities reported in the current study for BCS at both mating and weaning were within the range previously published for dual-purpose ewes (0.15-0.29, Everett-Hincks and Cullen 2009; Mekkawy et al. 2009; Shackell et al. 2011; Walkom et al. 2014). Shackell et al. (2011) and Everett-Hincks & Cullen (2009) both utilised a similar population to that used in the analysis of the current study of sheep from the SIL database, however, they considered BCS as a repeated measure across ages. Walkom and Brown (2017) and Brown et al. (2017) reported heritabilities for BCS in Merino and Merino-cross ewes that ranged from 0.11 to 0.25 at mating and 0.22 at weaning. Borg et al. (2009) reported a heritability of 0.13 of BCS at weaning in North American Targhee ewes (meat breed). These studies considered BCS as a repeated trait, whereas in the current study, BCS at mating and weaning as a two- and three-year old were considered as separate traits. Mekkawy et al. (2009) reported BCS at first mating as a two-year-old only, similar to that in the current study only reporting BCS at mating as a two- and three-year-old.

A repeated-measures design refers to the practice of measuring the outcome on each animal multiple times over a period of time (Zhao et al. 2019). In the current study, BCS was not analysed using a repeated measures design as the author was interested in the effect of the individual BCS measurements on production and the relationship between the different measures across multiple years. This had not been investigated in previous studies and would be useful information to identify which measurement, across the ewe's life, would be the most useful for selection purposes.

The greatest heritability estimate for BCS was at mating as a three-year-old, which is likely at a time when the ewe is nearing its mature live weight (Nasholm 1990;

Zygoyiannis et al. 1997; Annett et al. 2011; Pettigrew et al. 2019). Annett et al. (2011) reported that BCS at mating was greatest in three-year-old ewes and mature live weight was reached at four years of age. Heritability of BCS at mating was greater than the heritability of BCS at weaning in the study by Walkom and Brown (2017), in agreement with the results reported here in three-year old ewes.

5.1.7 Genetic and phenotypic correlations

The genetic variance of BCS ranged from 0.03 to 0.06 in the current study and was greatest at weaning as a one-year-old. In contrast, the residual variance in the current study was greater than this ranging from 0.15 to 0.25. The genetic variance was similar between BCS at mating and BCS at weaning, but the residual variance was greater at BCS at weaning due to environmental factors. Walkom and Brown (2017) reported phenotypic variance of 0.14 – 0.22 for BCS which is similar to that in this study, however as mentioned previously, BCS was treated as a repeated measure in that study. The genetic variance in the current study was consistent across ages one to three. This indicates a single BCS measurement will effectively account for majority of the genes that influence BCS throughout the year. Given that the BCS measurements are all highly genetically correlated (>0.50), it is unsurprising that the genetic variance is similar among BCS measurements.

As there is a strong genetic correlation observed between BCS at mating and BCS at weaning in successive production cycles, genetic gain for greater BCS could be made by imposing selection based on either measurement. It was reported by SIL (Sheep Improvement Limited 2016a) that one BCS measurement should be taken each year, preferably at mating. These results confirm that a single record of BCS each year is sufficient to assess and select for BCS. Based on the results of the current study it is recommended that BCS at mating should be recorded for selection purposes. Recording BCS at mating is also favorable for farmers as it is a time when they are likely to be looking at their sheep to make sure they are suitable for mating and there are not lambs to draft out of the flock as there would be at weaning time.

The phenotypic correlation between BCS at mating and BCS at weaning was low to moderate (0.17-0.51). Given that the phenotypic variance of BCS was greater at weaning, it makes sense that the phenotypic correlations between BCS and other traits were greater at mating than weaning. The greater phenotypic variance was due to environmental factors, such as lambing date, having more influence on BCS at weaning than at mating. The NLW will affect the ewe's nutritional needs (Nicol and Brookes 2007) resulting in twin-rearing ewes using more body fat, therefore, BCS units to produce milk for the lambs compared with single rearing ewes (Morel et al. 2016). These correlations were consistent with the findings of Shackell et al. (2011) in New Zealand crossbred ewes, as well as Walkom & Brown (2017) and Brown and Swan (2014) in Merino ewes.

In Chapter 3 it was recommended that farmers aim for BCS of 3.0 at mating for all sheep and that exceeding a BCS of 3.5 at any point throughout the year would not return increased production. Targeting an average genetic BCS of 3.0 in a flock would result in 95% of ewes that fall within a genetic BCS of 2.5 and 3.5 (representing 4 standard deviations based on $\widehat{\sigma}_g = 0.22$). However, these same 95% of the population will be phenotypically observed at a BCS that ranges approximately 1.88 to 4.16 (four standard deviations based on $\widehat{\sigma}_p = 0.55$). If both the genetic and residual variance could be reduced in the flock through selection, this could result in a smaller range of the genetic BCS, potentially also reducing the variance of the phenotypic BCS.

5.1.8 Number of lambs scanned and number of lambs weaned

Heritability of NLS in the current study was in agreement with the heritability of NLB reported in literature of 0.07-0.12 (Rosati et al. 2002; Borg et al. 2009; Pickering et al. 2012; Bunter and Brown 2015) and the heritability estimate for NLW was in agreement with Rosati et al. (2002) and Bunter and Brown (2015). In the current study, NLS is used as a proxy for NLB, therefore, these traits can be compared as there is a strong (98%) agreement between NLS and NLB (Farmer and Davis 1999). As the NLS and NLW heritabilities in the current study are in agreement with other reports then that means NLS in the current study can also be directly compared to NLB in other studies.

The genetic correlations between BCS at mating and NLS as a two- and three-year-old were negative (-0.23 to -0.15), indicating that a greater genetic BCS at mating would be seen alongside a genetically lower NLS. In contrast to the findings of the current study, Walkom and Brown (2017) reported a genetic correlation between mating BCS and NLS of 0.41 in Australian Merino ewes. A possible explanation for the difference between these two studies could be the difference in breed or that the birth and rearing rank were not fitted to BCS at mating in the current study.

The NLW relationship with BCS at mating and weaning at all ages had a large range that went through zero (-0.49 to 0.23). This, along with large standard errors indicate that the genetic correlations between BCS and NLW are likely to be close to zero. These results are supported by Walkom et al. (2016) in a breed composite and Walkom and Brown (2017) in Merino cross ewes. Walkom and Brown (2017) reported a genetic correlation between BCS at mating and NLW of -0.11±0.10.

5.1.9 Live weight

Estimates of heritability for liveweight at mating found in this study were lower than that reported previously (0.54-0.66, Shackell et al. 2011; Walkom and Brown 2017). The heritability for liveweight in the current study were similar to that reported (0.31) by Safari et al. (2005) in adult weight, from a review of studies reported over a 10 year period, and Mekkawy et al. (2009) at first mating (0.36) in Scottish Blackface and Hardy Speckled Face ewes. Shackell et al. (2011) only recorded live weight in 2009, whereas, the current study and Safari et al. (2005) recorded live weight over an eight-year period, including multiple generations of ewes.

There was a strong genetic correlation between liveweight at two- and three-years of age (0.95). The genetic correlations between BCS and liveweight were moderate (0.22-0.57). The correlations of BCS with live weight are important to be considered together due to the negative selection pressure on live weight (Sheep Improvement Limited 2019a), but a positive weighting on BCS (Sheep Improvement Limited 2019b). This would result in slower genetic gain for live weight and BCS, than if only live weight was considered. Sheep breeders should be aiming to balance the relationship between live weight and BCS. This balance is to ensure that live weight does not increase disproportionately to BCS which can be inefficient and becomes costly to maintain ewes at greater live weights. The balance also ensures that the lower live weight ewes maintain adequate BCS (above 2.5, Kenyon and Cranston 2017). This study has shown that if there were to be a positive or negative selection pressure put on BCS, live weight would also increase with minimal effects on NLS and NLW. Alternatively, if the current SIL dual-purpose selection index were to remain the same, the genetic BCS would slowly increase. This is a result of the positive genetic trends for ewe live weight, even though there is a negative weighting on live weight. Currently BCS is a sub-index in SIL, not requiring breeders to use it. Perhaps there should be a non-linear selection pressure placed on BCS in the NZMW to ensure ewes do not have high BCS, as this is inefficient and costly to maintain.

5.1.10 Weaning weight

Weaning weight (WWT) was considered in this study, similar to that in Shackell et al. (2011), to ensure there was no selection bias in the data (Pollak et al. 1984). Ewes selected for mating are likely to be those with the greatest WWT, as post-weaning live weight is strongly related to WWT (Baker et al. 1979; Neser et al. 2001). Heritability of WWT_m and WWT_d were in agreement with those previously reported of 0.12-0.21 (Neser et al. 2001; Safari et al. 2005; Borg et al. 2009; Pickering et al. 2012). Shackell et al. (2011) included WWT in the multivariate analysis, however, only reported WWT_d heritability of 0.23, which is slightly lower than that reported in the current study (0.30). Pickering et al. (2012) reported both WWT_m and WWT_d of 0.20 and 0.14 respectively, which were lower than that reported in the current study. Perhaps the reason for this is that Pickering et al. (2012) had a larger industry wide dataset and both sexes were represented in that dataset.

The genetic correlation between the direct effect and maternal effect on WWT was negative (-0.50) which has also been shown in previous studies (Willham 1972; Johnson et al. 1989; Tosh and Kemp 1994). The negative direct-maternal genetic correlation has been attributed to a range of different causes including missed effects in the model of estimation, sire by year interaction, data structure (Meyer

1992; David et al. 2015), genetic trade-offs (Abreu et al. 2018) and failure to model genetic variance. These negative genetic correlations have been related to slow genetic progress for WWT, however, David et al. (2015) showed that the influence of the direct-maternal genetic correlation on the total estimated breeding value was minimal.

The WWT_m is an indicator of milk production potential of the ewe (Willham 1972; Johnson et al. 1989) which will affect the growth and survival of the offspring. Genetic correlations between both WWT_d with live weight traits had been reported by Pickering et al. (2012). To the authors' knowledge, the genetic correlations of WWT_d and WWT_m with BCS has not been reported in literature. In the current chapter, it was found that the correlations of WWT_d or WWT_m with liveweight at mating were both positive even for three-year-old ewes. This means that the genes influencing WWT are similar to those influencing live weight at mating.

The genetic correlations between WWT_m and all the BCS measurements were moderate, however, the correlations between BCS and WWT_d were close to zero. This suggests that the genes of maternal ability are associated with the genes for the ewe BCS measurements across at least two age groups. Both the genetic and phenotypic correlations of WWT_d with NLS and NLW were low to negligible. This was in agreement with Pickering et al. (2012), that reported no phenotypic relationship between WWT_d and NLS and NLW, and a low genetic correlation between these traits.

Genetic correlations between WWT_m and BCS at mating was moderate (0.25-0.34). This means that the dams' influence on WWT was associated with their BCS later on, in that dams with greater genetic potential for milk production were more likely to produce offspring with greater genetic potential for BCS. In addition, ewes with greater potential for BCS are likely to have greater potential for milk production. Thus the maternal ability trait plays a role in the subsequent BCS of the flocks' replacement ewes. More research is required to confirm this relationship between WWT_m and BCS.

5.1.11 Limitations

The average BCS for the ewes in the current study was optimal for production (Kenyon et al. 2014). The average ewe live weight in the current study was slightly heavier than industry average (59 kg) live weight (Beef+Lamb New Zealand 2018) and the current chapter BCS were concentrated around BCS of 3.5, therefore, it would be interesting to see if the same genetic and phenotypic correlations exist in a flock with a lower mean BCS and live weight.

5.6 Conclusions

The purpose of the current study was to obtain estimates of heritability, phenotypic and genetic correlations of BCS, live weight and production traits in dual-purpose ewes. Heritability estimates of BCS reported in this chapter were similar to previous reports and indicate a moderate rate of genetic gain can be achieved for BCS if it were to be included in a selection index to ensure that BCS remains in the optimum range. The genetic correlations between BCS measurements were high, therefore, BCS could be recorded once a year for selection purposes. Body condition score should be included in the main NZMW and the economic weighting should be reviewed in light of BCS being an optimal trait and its correlation with live weight. How BCS should be geared in the index remains unknown. A repeated measures model will be used to analyse BCS in Chapter 7 to explore different methods of analysing BCS and BCS change.

6 Body condition score profiles of dual-purpose ewes in New Zealand

6.1 Abstract

Body condition score profiles could be a key identifier of production on farm. Five BCS measurements were used to predict BCS profiles across a 12-month period for 2,239 Romney ewes located near Te Anau from the years 2010 to 2017. The aim of this study was to identify different BCS profiles and determine if there were differences in production between these profiles. The analysis showed six different BCS profile clusters irrespective of parity. Five of the six profiles were characterised by a decrease in BCS from pregnancy scanning through to weaning and an increase in BCS from weaning to re-mating. The remaining profile (Cluster 5) did not exhibit a decrease in BCS and instead increased BCS steadily throughout the year. Ewes in cluster 5 were characterised by predominantly rearing singletons and having greater estimated energy requirements to TLW (total litter weaning weight) ratio compared to the other clusters. Greater TLW occurred if BCS loss occurred between mating and weaning, however, these ewes also had the greatest estimated energy requirements. Ewes in clusters 1 and 2 had greater ($P<0.05$) TLW and greater ($P<0.05$) energy requirements than ewes in clusters 3, 4, 5 and 6. Ewes in clusters 3 and 5 had greater ($P<0.05$) stayability to a four-year-old (0.74) than ewes in clusters 1 and 2. These results show that there are production differences between the six different BCS profile clusters within a sheep flock. Further information is required on the factors which determine the different BCS profiles and the lifetime performance of the ewe in a commercial flock.

6.2 Introduction

During periods of feed deficit, the animal mobilises body fat to meet maintenance, pregnancy and lactation requirements, and when feed supply increases, the body fat levels are restored (Bauman and Currie 1980; Bauman 2000; Blanc et al. 2006; Yilmaz et al. 2011). These levels of body fat are often estimated by using the body condition score (BCS) measurement. Body condition scores are frequently measured to observe and account for their aforementioned fluctuations (Russel et al. 1969). These fluctuations in BCS are frequently found in extensive grazing systems (Atti et al. 2001; Morris and Kenyon 2014; Morris and Hickson 2016).

It has been well documented that BCS can influence ewe reproductive performance and lamb performance (see review Kenyon et al. 2014; Chapter 3; Walkom et al. 2017). The information currently available compares BCS at a single point in time on the effect of single- and twin-bearing ewes (Chapter 3, Walkom et al. 2017; Mace et al. 2018a; Mace et al. 2018b). It was reported in chapter 3 that the change in BCS from weaning to mating and from scanning to weaning were related to the number of lambs weaned (NLW), lamb weaning weight (WWT) and total litter weight weaned (TLW). Previous research has not examined the relationships between different time periods, for example the effect of BCS change between mating and scanning on production is not known nor is the effect of a change, or lack of change, in BCS over a 12-month period on production.

A potential method of characterising fluctuations in BCS is to consider the profile of BCS measurements over one year. A BCS profile can be defined as the pattern of BCS each individual animal takes throughout one year as the ewe mobilises and deposits body fat. Previously, the change in BCS across the production year between individual measurements in Romane ewes has been grouped, based on this profile, into three clusters (Macé et al. 2019). The profiles followed similar periods of BCS gain and loss with the variation between profiles mainly due to increase in BCS during weaning and early pregnancy (Macé et al. 2018a). To the authors' knowledge there has been no published literature examining the effect of BCS profiles on ewe productive performance.

The energy required to increase 1 kg of live weight in ewes is approximately 55 MJ ME/kg, while only 30 MJ ME/kg is mobilised when live weight is lost (Nicol and Brookes 2007). Therefore, there is a net cost of 25 MJME/kg for each cycle of loss and gain in live weight. Thus, ewes which lose a significant amount of BCS (more than 1 BCS), require more feed to reach the same final BCS as the ewe that maintains throughout the year. For example, a ewe that changes from a BCS 3.5 at mating to 2.5 at weaning and then returns back to BCS 3.5 at mating, will require an extra 77 MJME of feed (equivalent to 1.3% of the total feed requirements for the year) than a ewe that maintains a BCS 2.5 due to feed requirements being met throughout the year (Nicol and Brookes 2007; Morel et al. 2016). It is therefore important to understand the productive performance of potentially different profiles a ewe may take to determine which is better in terms of productivity.

Chapter 4 and 5 showed that a single BCS measurement could be used for estimation of genetic parameters of BCS. Chapter 3 showed that BCS change between BCS measurements potentially has an effect on productive performance. However, the profile of BCS change over a year has not been considered. Therefore, the objectives of this chapter were to investigate the ewe BCS change throughout the year, identify the main BCS profiles and determine if there are differences in production between these profiles.

6.3 Materials and Methods

6.3.1 Dataset

Focus Genetics data was retrieved for the lambing year period of 2010 to 2017. Data from Freestone, a subset of the data used in the previous chapter, was extracted from Sheep Improvement Limited (SIL). There were 2,239 ewes with birth-year ranging from 2008 to 2015. Ewes born in 2008 were first presented for mating at 20-months of age. Ewes born between 2009 and 2012 were presented for mating at eight-months of age if they were of adequate live weight at pre-mating and all ewes born in 2012 or later were first presented for mating at eight-months of age. Ewes were managed under New Zealand commercial farming conditions. Ewes were culled if they were diagnosed as not pregnant at pregnancy scanning, were assisted at lambing or did not wean a lamb. Ewes were also culled based on their teeth, udder, feet, age or selection index.

Body condition score was recorded on a 1-5 scale (Jefferies 1961) in 0.5 increments, prior to mating in April (mating), at pregnancy diagnosis in July (scanning), prior to lambing in August (lambing) and at weaning in January (weaning). Ewes had both their sire and dam identity recorded based on DNA parentage discovery. Ewe age at lambing ranged from one to four years of age. Pregnancy scanning was recorded at approximately 75 days of pregnancy using ultrasound scanning and was recorded as the number of lambs scanned per ewe (NLS), ranging from zero to five. In this flock the number of lambs born was not recorded. Number of lambs weaned per ewe

(NLW) was the number of lambs per ewe present at weaning ranged from zero to five.

6.3.2 Data cleaning

Data were cleaned and traits were tested for normality as described in Chapter 5 to remove BCS records that were not whole or half scores between 0-5, ewes that had negative or zero RR values and one- and five-year-old ewes. The ewe records were separated into each year that they were present in the flock. There were 4,646 ewe-years included.

The production cycle was characterised as the BCS change through five measurements and these included mating, pregnancy scanning, lambing, weaning and the following years mating measurement (re-mating). Ewes were included if they had at least one BCS measurement within a year. Age at first lambing (AFL) was determined based on whether the ewe had a lamb recorded at one-year of age.

Ewe birth-rearing rank was classified according to the following combinations of her dam's NLS and NLW; scanned single and weaned single (1_1), scanned twin-bearing and weaned twins (2_2), scanned twin-bearing and weaned one lamb (2_1), scanned triplet-bearing and weaned triplets (3_3), scanned triplet-bearing and weaned twins (3_2) or single (3_1). For each ewe, average weight of lambs weaned (avWWT) and total litter weaning weight per ewe (TLW) was calculated from individual lamb weaning weight data.

6.3.3 Body condition score profile/model

A BCS profile was modelled for each ewe using a random regression model (RRM) with second-, third- and fourth-order Legendre polynomials using ASReml version 4.0 (Gilmour et al. 2015). The third-order polynomial had the best goodness of fit based on the Akaike information criterion (AIC) and Bayesian information criterion (BIC). The smaller the AIC and BIC out of the models run, indicates the least information is lost by the model.

The RRM was the following.

$$y_{it} = \sum_{k=0}^{3} \beta_k P_{kt} + \sum_{k=0}^{3} a_{ki} P_{kt} + e_{it}$$

Where y_{it} = BCS of ewe i in month t; β_k is the fixed regression coefficient of BCS on month of production cycle; a_{ki} is the k^{th} random regression coefficient for ewe-year i on month t of the production year; P_{kt} is the normalized function of x at month t calculated as:

$x = 2\left(\frac{t-t_{min}}{t_{max}-t_{min}}\right) - 1$ (Sivestre et al. 2009), and the P_{kt} values calculated as:

$p_0(t) = 1, p_1(t) = x, p_2(t) = \frac{1}{2}(3x^2 - 1), p_3(t) = \frac{1}{2}(5x^3 - 3x)$ (Silvestre et al. 2009).

In the current study $t_{min} = 0$ months and $t_{max} = 12$ months so the BCS records between 0-12 were converted into the interval of -1 to 1. e_{it} is the random residual error assumed to have a homogenous variance.

Predicted values of BCS for each ewe and each year were calculated using the estimates of the random regression coefficients for each ewe-year. Other measures of goodness of fit were the coefficient of determination (r^2) and the relative prediction error (RPE, O'Neill et al. 2013). The mean prediction error (MPE) and RPE were calculated as follows.

$$MPE = \sqrt{MSPE}$$

$$RPE(\%) = \left(\frac{MPE}{A_m}\right)$$

Where A_m is the mean actual BCS, MSPE is the mean square prediction error and is the sum of three components. The mean bias, line bias and random variation. These are represented in the equation:

$$MSPE = (A_m - P_m)^2 + S_p^2(1 - b)^2 + S_A^2(1 - r^2)$$

Where A_m and P_m are the means of the actual and predicted BCS, respectively. S_A^2 and S_p^2 are the variances of the actual and predicted BCS, respectively. b is the slope of the regression of actual on predicted, and r is the correlation coefficient of actual and predicted.

The three components as mentioned previously are the mean bias ($A_m - P_m$), the line bias (b), which is the deviation of the slope of the regression of actual on predicted from unity ($1 - b$), and random variation around the regression line ($1 - r^2$).

The smaller the RPE the more accurate the predictions are.

6.3.4 Cluster analysis

Cluster analysis was performed in order to investigate the variability of individual BCS profiles for each production year (Macé et al. 2019). The random regression coefficients for each animal and year obtained from the random regression model were used for cluster analysis using SAS 9.4 (SAS Institute Inc, Cary NC, USA). The method of clustering used was k-means, where a set number of clusters is specified and then that same number of 'centroid' or mean positions are recalculated until convergence is met to minimise the sum of squares estimate of errors (SSE) of each cluster (Schwager et al. 2007). Pseudo f statistic is the ratio of between cluster variance to within-cluster variance (Caliński and Harabasz 1974), the lower the number, the lower the distance between each random regression coefficients within each cluster. The r^2 reflects the differences between clusters. Two to eight clusters were tested and the number of clusters selected was determined using the pseudo f statistic and r^2.

Least-squares means of age, age of dam (AOD), NLS, NLW, avWWT and TLW for each BCS profile were obtained and used for multiple mean comparisons using the Fisher's least-significant-difference test.

6.3.5 Transitional Probabilities

Using SAS 9.4 (SAS Institute Inc, Cary NC, USA), transitional probabilities between clusters were calculated based on the number of ewes in each cluster at ages two, three and four. An additional cluster was added (Cluster 7) where, if the ewe did not have a BCS measured at the following mating, given that the previous year had records, then it was assumed that ewe was removed from the flock i.e. it was assumed the end of the ewes' productive life. The 2015 born ewes were not included in this calculation as they only had one year of data therefore it could not be determined if they remained in the flock or not.

6.3.6 Ewe productivity and stability

Production, stayability and energy requirements were used to compare the six clusters of BCS profiles. More information on the calculations used and energy requirements are presented in Appendix One. Production was taken as the TLW and the stayability was treated as a binomial trait where the ewe either remained in the flock or was removed. The energy requirements were estimated as follows. Maintenance requirements were calculated based on the average BCS across the BCS profile and converted into live weight (1-unit BCS change = 7.3kg, Morel et al. 2016). The energy required for pregnancy was estimated on an assumed average lamb birth weight of 4kg (Pettigrew et al. 2018), which equates to an extra 200 MJME per lamb (Nicol and Brookes 2007), multiplied by the NLS for each ewe. The total lactation requirements were calculated based on an average avWWT of 35kg (1625 MJME, Nicol and Brookes 2007), multiplied by NLW for each ewe. The BCS change was calculated on a monthly basis for each cluster. A loss of BCS released 30 MJME per unit BCS and a gain in BCS required 55 MJME per unit BCS (Morel et al. 2016). The total energy requirements were the sum of the maintenance, pregnancy, lactation and BCS change requirements (Nicol and Brookes 2007).

Least-squares means of average BCS across the profile, change in BCS (ΔBCS) between mating and the following re-mating, ΔBCS over the first month of lactation (early lactation), ΔBCS over the lactation period (lactation), ΔBCS from weaning to re-mating (post-lactation), TLW, stayability to three-years-old, stayability to four-years-old, estimated energy requirements and estimated energy requirements per kilogram of lamb per ewe for each cluster were obtained and used for multiple mean comparisons using the Fisher's least-significant-difference test.

6.4 Results

The number of records for BCS measurements was greatest at pregnancy scanning and least at lambing (Table 6.1). Weaning BCS ranged 1.0 to 5.0 and pregnancy scanning ranged 2.0 to 5.0.

Table 6.1. Number of ewe-years, mean, standard deviation, minimum and maximum for New Zealand Romney ewe body condition score (BCS) at Mating, Pregnancy scanning, Lambing, Weaning and Mating the following year (Re-mating).

	n	mean	SD	min	max
BCS					
Mating	4339	3.47	0.46	1.5	5.0
Pregnancy scanning	4542	3.56	0.44	2.0	5.0
Lambing	2126	3.62	0.42	1.5	5.0
Weaning	3591	3.12	0.57	1.0	5.0
Re-mating	2614	3.46	0.48	1.5	5.0

6.4.1 Comparison of models

The model with the lowest AIC and BIC was order 4 (Table 6.2), however, order 4 was only slightly better than order 3. The r^2 and RPE are similar between order 3 and order 4 (Table 6.2). Due to the significant increase in computational power required with order 4 as a result of an extra parameter, the bias between models was examined.

Table 6.2. Prediction accuracy of Legendre polynomials of order two, three and four for the prediction of body condition score of New Zealand Romney ewes.

Polynomial	AIC	BIC	r^2	RPE (%)
Order 2	-8397.27	-8343.06	0.59	9.44
Order 3	-10840.51	-10755.32	0.73	7.73
Order 4	-11484.02	-11360.11	0.75	7.46

AIC: Akaike information criterion, BIC: Bayesian information, r^2: the coefficient of determination, RPE: Relative prediction error

The average actual and predicted BCS for each model was similar which was reflected in the overall bias of each model (Table 6.3). The mean, line and random bias are presented in Table 6.3. Order 3 and 4 show similar line and random bias. A third-order Legendre polynomial was selected and fitted to the data for subsequent analysis.

Table 6.3. Prediction accuracy of the model for predicted the body condition score (BCS) profile of New Zealand Romney ewes.

Polynomial	Actual BCS	Predicted BCS	Slope	Bias	MSPE[1]	Mean bias	Line bias	Random variation	MPE[2]
Order 2	3.43	3.42	0.38	0.01	0.11	0.01	0.59	0.39	0.32
Order 3	3.43	3.42	0.55	0.01	0.07	0.01	0.62	0.37	0.27
Order 4	3.43	3.44	0.58	0.01	0.07	0.01	0.62	0.37	0.26

[1]MSPE, Mean square prediction error. [2]MPE, Mean prediction error

A third order Legendre polynomial was fitted to the ewe-year BCS data. The predicted BCS was plotted against the actual BCS for the third order Legendre polynomial (Figure 6.1). There is a slight underestimation at higher BCS range of scale and an overestimation of the lower BCS end.

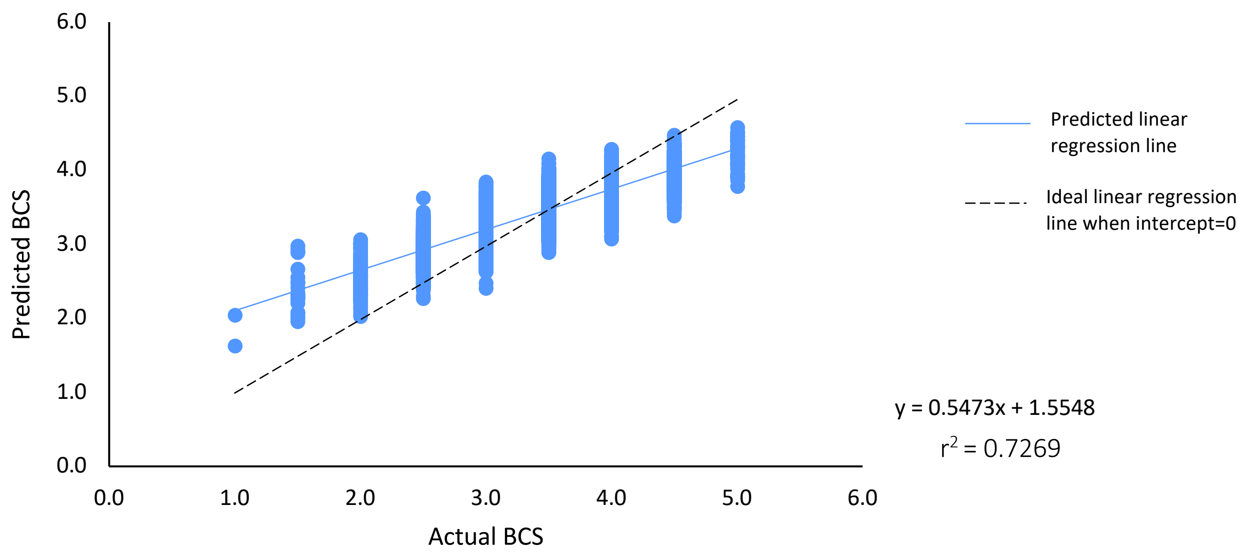

Figure 6.1. The predicted body condition score (BCS) fitted against the actual BCS of New Zealand Romney ewes for the prediction equation obtained from the order 3 Legendre polynomial. The linear regression line equation is shown on the graph. The ideal linear regression line if the intercept were zero and the slope was 1 is also displayed (dashed line).

6.4.2 Cluster analysis

The r^2 increased as the number of clusters increased. Six clusters were used for further analysis. The greater r^2 the better model fit, given the pseudo f statistic is the lower number, as the r^2 will continue to increase until each animal is in its own cluster.

Table 6.4. Prediction accuracy of the cluster analysis for predicted body condition score (BCS) for three to eight cluster profiles of New Zealand Romney ewes.

	Number of clusters					
	3	4	5	6	7	8
Pseudo F Statistic	2726	2712	2642	2534	2639	2612
r^2	0.54	0.64	0.70	0.74	0.78	0.80

r^2: the coefficient of determination

The r^2 is above 0.70 for all models above five clusters, therefore, a cluster above five should be chosen. The profiles were grouped into six clusters as the pseudo f statistic decreased at six clusters before increasing again at seven.

The BCS profiles were clustered into six groups (Figure 6.2). Clusters 1, 2 and 6 are characterised by a slight increase in BCS from March to May, followed by a loss in BCS to December and then a gain in BCS between December to March. Clusters 3 and 4 follow a similar pattern to each other, however, differ by a BCS of 0.5 with cluster 3 being higher than cluster 4. Cluster 5 differs from all others, where the BCS profile increases throughout the production year starting at a BCS of approximately 3.5 at mating in March and ending at approximately 4.0 at re-mating the following March.

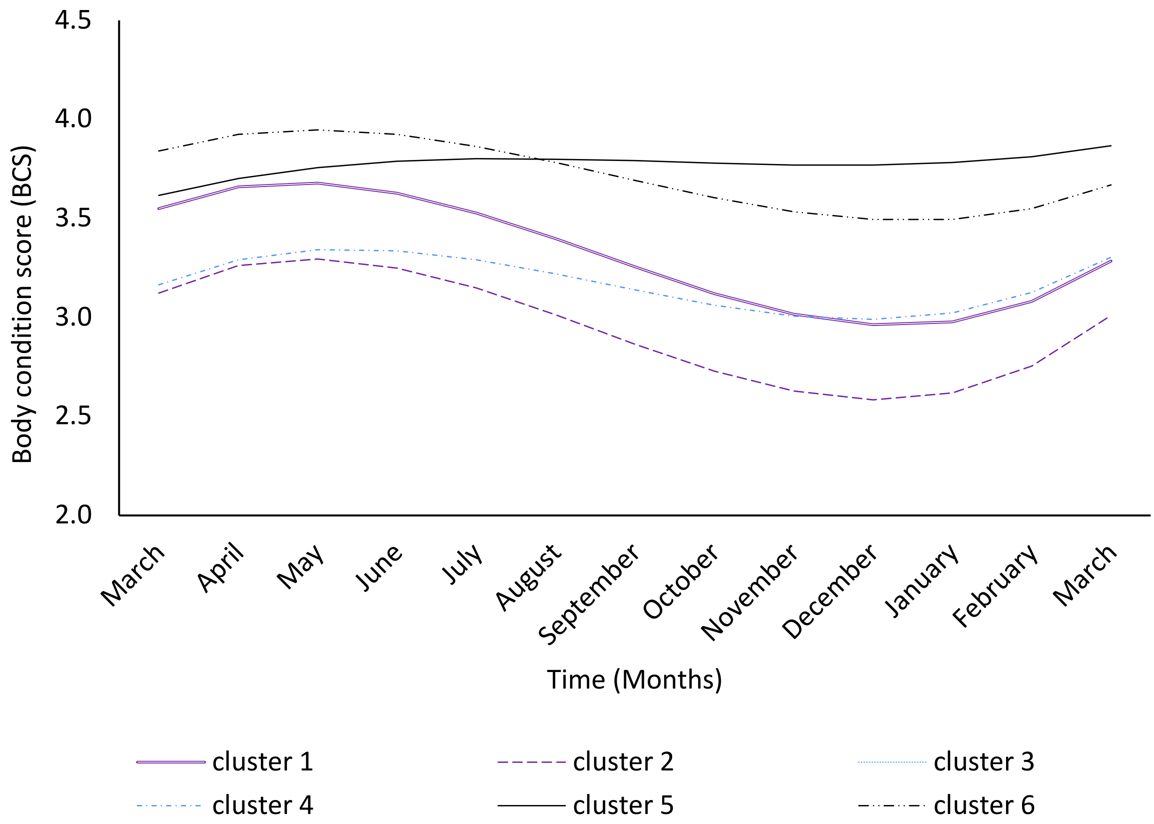

Figure 6.2. New Zealand Romeny ewe mean BCS profiles of six clusters. Cluster 1 (purple solid), cluster 2 (purple dash), cluster 3 (blue dot), cluster 4 (blue dash and dot), cluster 5 (black solid) and cluster 6 (black dash and double dot).

Cluster profile differences

Ewes in clusters 5 and 6 had greater (P<0.05) average BCS across the production year than ewes in clusters 1, 2, 3 and 4 (Table 6.5). Ewes in cluster 5 had the greatest (P<0.05) positive BCS change across the production year compared with ewes in all other clusters. Ewes in clusters 1 and 2 had a greater decrease in BCS during early lactation compared with ewes in clusters 3, 4, 5 and 6. Ewes in cluster 5 had the least (P<0.05) BCS change across lactation, followed by ewes in clusters 3 and 4 then ewes in cluster 6, with ewes in clusters 1 and 2 having the greatest (P<0.05) BCS change. Ewes in cluster 2 had the greatest (P<0.05) BCS increase post-lactation (0.43 units) compared with ewes in cluster 5 which had the least (P<0.05).

Table 6.5. Least squares mean of the average BCS of New Zealand Romney ewes across the production year, change in BCS (ΔBCS) between mating and the following re-mating, ΔBCS over the first month of lactation (early lactation), ΔBCS over the lactation period (lactation) and ΔBCS from weaning to re-mating (post-lactation) for each cluster.

Cluster	Average BCS	ΔBCS mating to mating	ΔBCS early lactation	ΔBCS lactation	ΔBCS post-lactation
1	3.32±0.01[c]	-0.27±0.01[d]	-0.14±0.001[d]	-0.30±0.002[d]	0.32±0.002[b]
2	2.94±0.01[e]	-0.12±0.01[c]	-0.14±0.001[e]	-0.29±0.003[e]	0.43±0.002[a]
3	3.45±0.01[b]	0.04±0.01[c]	-0.07±0.001[b]	-0.15±0.001[b]	0.24±0.001[c]
4	3.18±0.01[d]	0.14±0.01[b]	-0.08±0.001[c]	-0.15±0.002[b]	0.32±0.001[c]
5	3.77±0.01[a]	0.25±0.01[a]	-0.01±0.001[a]	-0.02±0.003[a]	0.10±0.002[d]
6	3.72±0.01[a]	-0.17±0.01[d]	-0.09±0.001[c]	-0.20±0.002[c]	0.18±0.001[c]

[a, b, c, d, e] Means with different superscript within column are significantly different (P<0.05).

The average BCS for all measurements for ewes in cluster 3 were all very similar between the actual and predicted average values (Table 6.6). The lambing, weaning and re-mating BCS measurements for ewes in cluster 4 were also similar between the actual and predicted. Ewes in clusters 2 and 4 had the lowest beginning BCS and tended to overestimate average BCS. Ewes in cluster 6 tended to underestimate average BCS at each measurement period. The predicted BCS for cluster 5 tended to underestimate the actual BCS at weaning and following mating.

Table 6.6. Actual body condition score (BCS) of New Zealand Romney ewes compared with the predicted BCS for each cluster profile at mating (Mate), pregnancy scanning (Scan), lambing (Lamb), weaning (Wean) and re-mating (Remate).

		Mate	Scan	Lamb	Wean	Remate
Cluster 1	actual	3.70	3.70	3.57	2.70	3.19
	predicted	3.55	3.63	3.40	2.92	3.29
Cluster 2	actual	3.04	3.15	3.13	2.31	2.84
	predicted	3.12	3.27	3.02	2.54	3.02
Cluster 3	actual	3.46	3.56	3.68	3.29	3.57
	predicted	3.47	3.62	3.51	3.26	3.52
Cluster 4	actual	3.00	3.17	3.22	2.93	3.38
	predicted	3.17	3.35	3.23	2.96	3.31
Cluster 5	actual	3.59	3.71	3.91	4.03	4.05
	predicted	3.62	3.80	3.80	3.76	3.87
Cluster 6	actual	4.07	4.05	3.96	3.43	3.70
	predicted	3.84	3.92	3.79	3.47	3.68

6.4.3 Comparison of profiles

The greatest number of ewes were in cluster 3 (Table 6.7). Ewes in clusters 5 and 6 had greater ($P<0.05$) ewe age than ewes in clusters 1, 2 3 and 4. There was no difference ($P>0.05$) in AOD between the clusters (results no shown). Cluster 1 and 2 ewes had greater ($P<0.05$) NLS and greater ($P<0.05$) NLW than ewes in clusters 3, 4, 5 and 6. Ewes in cluster 5 had the greatest ($P<0.05$) avWWT out of all the clusters. Cluster 1 and 2 ewes had the greatest ($P<0.05$) TLW compared with ewes in clusters 3, 4 and 6, whilst cluster 5 ewes had the least.

Table 6.7. Least-squares means of New Zealand Romney ewe age, number of lambs scanned (NLS), number of lambs weaned (NLW), average litter weaning weight (avWWT) and total litter weaning weight (TLW) for cluster one to six.

Cluster	n	age	NLS	NLW	avWWT	TLW
1	539	2.62 ± 0.03^{bc}	2.39 ± 0.03^{a}	1.98 ± 0.03^{a}	34.15 ± 0.30^{c}	66.99 ± 0.88^{a}
2	434	2.53 ± 0.04^{c}	2.42 ± 0.03^{a}	2.03 ± 0.04^{a}	33.17 ± 0.32^{d}	68.31 ± 0.98^{a}
3	1474	2.67 ± 0.02^{b}	2.17 ± 0.02^{b}	1.68 ± 0.02^{c}	35.47 ± 0.20^{b}	59.81 ± 0.61^{b}
4	801	2.57 ± 0.03^{c}	2.19 ± 0.02^{b}	1.76 ± 0.03^{b}	34.56 ± 0.28^{c}	61.00 ± 0.86^{b}
5	433	2.82 ± 0.04^{a}	2.02 ± 0.03^{c}	1.20 ± 0.04^{d}	37.39 ± 0.35^{a}	50.12 ± 1.09^{c}
6	622	2.83 ± 0.03^{a}	2.18 ± 0.03^{b}	1.61 ± 0.04^{c}	36.00 ± 0.34^{b}	60.15 ± 1.04^{b}

$^{a, b, c, d}$ Means with different superscript within column are significantly different ($P<0.05$).

6.4.4 Transitional probabilities

The probability of a ewe transitioning from one cluster profile to another cluster profile is shown in Table 6.8 as a ewe ages from a two- to a three-year-old and in Table 6.9 from a three- to a four-year-old ewe. Cluster 3 ewes are most likely to remain in cluster 3 (0.31) or exit the flock as cluster 7 (0.32). Ewes in the least productive cluster profile (cluster 5) were most likely to move into cluster 6 which was slightly more productive than cluster 5.

Table 6.8. Transitional probabilities of New Zealand Romney ewes from a given cluster profile to another as the ewe ages from two to three years old.

			Three-year-old Cluster						
		n	1	2	3	4	5	6	7
Two-year old Cluster	1	303	0.04	0.10	0.29	0.25	0.06	0.03	0.23
	2	249	0.02	0.15	0.19	0.36	0.04	0.00	0.24
	3	594	0.08	0.03	0.31	0.04	0.10	0.12	0.32
	4	336	0.06	0.06	0.30	0.13	0.07	0.03	0.35
	5	160	0.07	0.00	0.10	0.00	0.16	0.41	0.26
	6	205	0.10	0.01	0.24	0.02	0.17	0.17	0.29

Cluster 7: Exited the flock

Cluster 1 two-year-old ewes that exhibit the greatest TLW, had a 14% (0.04 + 0.10, Table 6.8) chance of being high the following year (remaining in cluster 1 or 2) and a 23% chance of exiting the flock (cluster 7). Similarly, cluster 2 two-year-old-ewes have a 17% (0.02 + 0.15) chance of remaining in cluster 1 or 2 as a three-year-old. The most likely outcomes for cluster 1 and 2 ewes were to move to cluster 3 and cluster 4, respectively regardless of age. There are nine percent of ewes that move from cluster 1 as a three-year-old to cluster 5 as a four-year-old (Table 6.9).

Table 6.9. Transitional probabilities of New Zealand Romney ewes from a given cluster profile (1-6) to another as the ewe ages from three to four years old.

			Four year old Cluster						
		n	1	2	3	4	5	6	7
Three-year old Cluster	1	114	0.05	0.08	0.29	0.22	0.09	0.10	0.17
	2	105	0.00	0.24	0.06	0.29	0.00	0.00	0.41
	3	429	0.13	0.02	0.24	0.05	0.06	0.10	0.40
	4	218	0.06	0.06	0.24	0.10	0.03	0.02	0.49
	5	167	0.08	0.01	0.10	0.01	0.11	0.39	0.30
	6	117	0.09	0.01	0.17	0.01	0.17	0.24	0.31

Cluster 7: Exited the flock

For both two-year-old and three-year-olds, none of the ewes in the lowest average BCS cluster profile (cluster 2, 2.94) moved to the highest BCS cluster profiles (cluster 5 and 6), as this would require a large increase in BCS. Additionally, clusters 5 and 6 had a low chance (7-10%, Table 6.8) of moving to cluster 1 or 2 thereby were unlikely to substantially increase production as a three-year-old.

Clusters 1 and 2 had greater ($P<0.05$) TLW and greater ($P<0.05$) estimated energy requirements than clusters 3, 4, 5 and 6 (Table 6.10). Clusters 3 and 5 had greater ($P<0.05$) stayability to four-years-old (0.74) than ewes in clusters 1 and 2. Cluster 5 had greater estimated energy requirements to TLW ratio compared to the other clusters.

Table 6.10. Stayability given the New Zealand Romney ewes were present in the flock as two-year-olds, and estimated energy requirements (MJME) for each cluster of BCS profiles based on the litter size and TLW.

Cluster	Stayability to a 3-year-old	Stayability to a 4-year-old	Energy requirements	Energy/TLW
1	0.78±0.02	$0.51±0.03^{b}$	$7906±65^{a}$	127.52^{c}
2	0.77±0.03	$0.50±0.03^{b}$	$7892±73^{a}$	125.35^{c}
3	0.74±0.02	$0.59±0.02^{a}$	$6932±40^{b}$	137.64^{b}
4	0.74±0.02	$0.57±0.02^{ab}$	$6994±55^{b}$	136.86^{b}
5	0.75±0.03	$0.56±0.04^{ab}$	$6762±73^{c}$	153.01^{a}
6	0.78±0.03	$0.63±0.03^{a}$	$6513±61^{c}$	136.29^{b}

$^{a, b, c}$ Means with different superscript within column are significantly different ($P<0.05$).

6.5 Discussion

The BCS profiles in the current study describe BCS change over time for a given ewe rather than individual BCS at specific time points within a given production year (Chapters 4 and 5). The changes in BCS throughout the year occurred due to seasonal changes in feed supply and the variation among animals for pregnancy and lactation energy requirements. In this study ewes within the farm were managed as one cohort without any attempt to manipulate a given ewes BCS profile over the production year.

Modelling BCS profiles is not a new concept in ruminants, having been utilised many times in dairy cattle (Berry et al. 2003; Banos et al. 2004; Berry et al. 2006; Roche et al. 2006). There are only a few studies to date that have modelled the BCS profile of sheep (Macé et al. 2019). In dairy cattle the BCS profile from one calving to the next was analysed due to its importance of milk production. In sheep production systems in New Zealand, the growth of the lamb is the important determinant of production and profit (Hawkins and Wu 2011). Therefore, the focus is often from mating to weaning of the lamb, however, sheep are managed on a multi-year basis. Thus, the current study also examined the BCS profile from mating to the following re-mating.

6.5.1 Comparison of models

The line bias is the slope of the regression of actual BCS and predicted BCS. The slope of 0.55 was less than 1.0, which indicated that the model tended to under-predict BCS at the low end of actual values and tended to over-predict at the high end. When the source of error in the prediction was investigated, the line bias as a proportion of the MSPE was 0.62 and the random variation proportion of the MSPE was 0.37. This indicated that the line bias was slightly greater than the random variation as a proportion of the MSPE. Even though the line bias is slightly higher than ideal, the RPE is still low at 7.73%.

6.5.2 Body condition score profile differences

The greatest number of ewes were in cluster 3 (Table 6.7), which was to be expected in a commercially operated farm where the industry target BCS is 3.5 at mating (Kenyon and Cranston 2017). Cluster 3 began and finished at a BCS of 3.5. Most ewes followed similar profiles throughout the three production years of this study. This agrees with Macé et al. (2019), who reported that for the clusters that decreased in BCS towards weaning (Clusters 1 and 2), the average litter size was higher.

6.5.3 Body condition score profiles production

As the number of foetuses carried increases, so do the energy requirements (Freer et al. 2007; Nicol and Brookes 2007). The triplet-rearing ewes often lose more BCS than single- and twin- bearing ewes during lactation as there is a greater energy demand for milk production. The difference in energy balance then comes from mobilisation of fat (Vernon et al. 1981; Bell 1995; Chilliard et al. 2000). This would explain the lower average BCS cluster profiles having the greatest production.

The NLW and avWWT per ewe is a key determinant of farm profitability (Morel and Kenyon 2006; Hawkins and Wu 2011). TLW is a combination of NLW and avWWT per ewe lambing (Mathias-Davis et al. 2011). This study used TLW as a determinate of ewe production. Clusters 1 and 2 have the greatest TLW. Greater TLW is good for increasing farm profit, however, larger losses in BCS (e.g. 1 BCS unit) between mating and weaning will result in a greater BCS gain required between weaning and re-mating to return to the starting BCS compared to ewes that only lose 0.5 unit of BCS. As there is a demand for higher feeding levels post-weaning for both lambs and ewes, the lambs are often the priority stock class, leaving the ewes to regain BCS on low quality feed or in many regions of New Zealand, restricted feed due to dry conditions limiting pasture growth (Radcliffe 1974; Rattray 1978; Morris and Kenyon 2014). Potentially as a result of restricted feed or low-quality feed, ewes either decrease production the following year moving to cluster 3 or cluster 4, or exit the flock (cluster 7).

A previous mention of BCS profiles in sheep was made by Macé et al. (2018a) and Macé et al. (2019) where the change in BCS between eight BCS measures per production year of around 250 Romane ewes was examined. The change in BCS values were clustered in the study by Macé et al. (2018a) to obtain three different BCS profiles, whereas in the current study there were six clusters. The study by Macé et al. (2018a) had more BCS points (eight per year) but only 250 ewes. The current study looks at 2,239 ewes with four yearly BCS measurements over the same number of production cycles (three litters).

6.5.4 Change in BCS profile cluster

Macé et al. (2019) showed that the ewes were more likely to remain in a similar cluster or move to a cluster with a lower BCS profile which was in agreement with the current study. Clusters 1, 2 and 6 all followed the same trend, with similar periods of BCS gain and loss. However, they differed by the starting BCS of each profile being 3.0, 3.5 and 4.0, respectively. Cluster 2 ewes would first have to go through Cluster 1 before being able to move to Cluster 6. This is unlikely to occur as a four-year-old would have to be fed above requirements throughout the year to increase BCS the required 1.0 BCS unit while still weaning a lamb.

Cluster 5 has a very different BCS profile from the others. Within this cluster ewes maintain BCS throughout the year which shows in the production of the ewes in cluster 5. These ewes have the lowest TLW and rear the least lambs (1.20 lambs/ewe). These are the least desirable ewes from a farmers point of view and fortunately only make up 10% of the flock. Cluster 5 ewes often come from the same cluster the previous year or from Cluster 6, which is the cluster with a similar average BCS to Cluster 5. Cluster 6 maintains a high BCS with a smaller litter size and lower TLW than Clusters 1 and 2. The clusters with lower production are likely to have low milk production potential (Borg et al. 2009), therefore, are unlikely to lose BCS to provide energy for milk production.

The greatest average BCS profile (Cluster 5) has a low chance (7-10%) of having an increase in production the following year and moving to Cluster 1 or 2, indicating that it is unlikely that the ewes in Cluster 5 are going to increase in production in subsequent years.

It appears that ewes that have the greatest production are those that lose the greatest BCS as a result of using the fat energy for milk production. However, it is unclear whether the decrease in BCS results in greater production due to the ewe partitioning more energy towards milk production or the ewes with greater NLS and NLW (i.e. triplet-bearing ewes) requiring more energy to support milk production thus causing a decrease in BCS. This could be tested by running the analysis on twin-bearing ewes only. Macé et al. (2019) found a similar three clusters when only analyzing the twin-bearing ewes compared with the whole population clusters. This indicated that the NLS and NLW were not the only factors determining the BCS profile of the ewe.

The other factors that could explain the different BCS profiles between the clusters is the milk production potential and feed supply. If the feed supply does not meet the demand for milk production then BCS will decrease. This could occur in ewes at any litter size, although seems more likely to occur for greater litter sizes as there is often insufficient glucose as a proportion of total ME intake for adequate lactation

(Banchero et al. 2004). Therefore, BCS loss occurs to maintain energy balance (Vernon et al. 1981; Bell 1995; Chilliard et al. 2000).

6.5.5 Goodness of fit

Fuentes-Pila et al. (1996) considered a model to be a satisfactory fit when the RPE was less than 10%, therefore, the third-order Legendre polynomial for predicting BCS profiles in the current study was good (less than 5%). A downside to fitting BCS profiles using a polynomial is the underestimation of the prediction of BCS above 3 and overestimating the prediction of BCS below 3 (Figure 6.1). This results in the dips and peaks of the predicted BCS profiles being smaller than the actual BCS values at these points. The slight difference in prediction compared with the actual BCS measurements, however, did not affect the cluster that each ewe was classified in.

6.5.6 Limitations

There were fewer BCS records at lambing due to this measurement no longer being recorded from 2013 as the selection index for BCS was based on only the mating BCS (Sheep Improvement Limited 2016b). Pregnancy scanning and weaning BCS have continued to be collected most likely due to the sheep being brought into the yards at these times for other reasons allowing for BCS to be recorded. These measurements are commonly collected to allow farmers to alter feeding management for their sheep in the following months.

This population of sheep were from a commercially run farm, therefore, their BCS is likely to be heavily influenced by feed supply and, as discussed, could partly explain the different BCS profiles. It would be interesting to study sheep that were fed supplements to try and reduce the low point of the BCS profile to minimise the loss in condition through to weaning resulting in less BCS gain required prior to re-mating. This would allow testing of BCS profiles without the limitation of feed supply. This would be useful to determine if ewes still exhibit the differing production while following a similar BCS profile.

6.6 Conclusions

There were six different BCS profiles identified that had different avWWT and TLW. Ewes that maintained BCS above 3.5 displayed the lowest production and made up 10% of the flock. Greater TLW occurred if BCS loss occurred between mating and weaning, however, these ewes also had the greatest estimated energy requirements. More research around the lifetime productivity of each BCS profile needs to be considered to determine the optimum ewe BCS profile.

7 Genetics of body condition score profiles and production traits

7.1 Abstract

Body condition score (BCS) fluctuates as the ewe mobilises and deposits body fat during a production year. The profile of BCS can be affected by environmental and genetic factors. To determine genetic parameters of BCS throughout a production year (mating, pregnancy scanning, lambing, weaning and the following mating), a random regression model was used. Fixed effects were contemporary group (measurement year and event), birth-rearing rank, the combination of number of lambs scanned and number of lambs weaned, parity, age at first lambing, age of dam, and month of measurement modeled with a third order Legendre polynomial. Random effects were animal additive genetic, modeled across months of measurements with a third order Legendre polynomial, ewe permanent environment separated within parity and across parities, and the residual error. The BCS heritabilities across the year were estimated to be moderate, and ranged from 0.20 to 0.30. The estimated heritabilities of BCS in dual-purpose ewes indicate that BCS could be used in a genetic evaluation for that population. The estimated heritabilities of BCS change were low indicating that the ability to alter the shape of BCS profiles by selection remain limited. The inclusion of BCS in the New Zealand Maternal Worth selection criteria has some merit to improving ewe BCS, however, the economic importance of BCS in the current index requires further investigation.

7.2 Introduction

Changes in body condition score (BCS) over a 12-month period (production year) reflect the short- to medium-term nutritional status of a ewe (Van Burgel et al. 2011). In New Zealand, the current selection scheme for dual-purpose sheep is called the Maternal Worth Index (NZMW) which includes reproduction, survival, lamb growth, mature adult live weight and wool traits (Sheep Improvement Limited 2019c). The selection criterion does not currently include BCS, although, BCS is recorded once or twice during the year i.e. at mating and/or weaning BCS into the national database (Sheep Improvement Limited 2019b) BCS is available as a sub-index for those breeders who wish to include it in their selection criteria.

Phenotypic BCS profiles were characterised (Chapter 6) and these results indicated that there were six profiles for individual ewes over a 12-month period. A BCS profile can be defined as the pattern of BCS which an individual animal shows throughout one production year (Berry et al. 2006; Macé et al. 2019) and can provide additional information on BCS genetic parameters than BCS measured at one or two times across the production year. Body condition score fluctuates as the ewe mobilises and deposits body fat (Macé et al. 2018a; Macé et al. 2018b) and is affected by numerous environmental and management factors (Chapter 2, Kenyon et al. 2004b; Morel et al. 2016; Kenyon and Cranston 2017). The differences in the phenotypic BCS profile between clusters (Chapter 6) were influenced by production, however, the effect that genetics has on the phenotypic BCS profiles was not known.

The genetic parameters for change in BCS between two time points have previously been considered. Walkom and Brown (2017) in Australian Merino crossbred ewes reported a low heritability (0.03-0.06) for change in BCS between mating and weaning. Similarly, Macé et al. (2018b) and Macé et al. (2018a) found in French Romane ewes that the heritability of BCS change was also low to moderate (0.04-0.16). Combined, these studies indicate that genetics explains only a small proportion of the variation in change in BCS measurements between two time points. There appears to be no reports of month-by-month genetic parameters for BCS. The objective of this study was to determine the genetic variances for BCS across the production year.

7.3 Materials and Methods

7.3.1 Animals and measurements

The ewe data utilised was from the Freestone farm, located near Te Anau in the South Island of New Zealand (Figure 6.1) and was extracted from the Sheep Improvement Limited (SIL) database. Data were included from 1,553 ewes that had 159 sires. Birth year ranged from 2008-2016, ewe age ranged from one to five years. Ewes had both their sire and dam recorded and DNA was collected from the ewes and their resulting lambs to determine parentage.

Body condition score was recorded between 2008 to 2017 on a 1-5 scale (1=emaciated and 5=obese, Jefferies 1961) in 0.5 increments, prior to mating in April (mating), at pregnancy diagnosis in July (scanning), prior to lambing in August (lambing) and at weaning in January (weaning). Live weight of ewes was recorded prior to mating only. The number of lambs scanned per ewe (NLS) was based on the number of lambs recorded at pregnancy diagnosis using ultrasound scanning at approximately 75 days of pregnancy (as per SIL database procedure, Sheep Improvement Limited 2019c) and ranged from one to six. Rearing rank or number of lambs weaned per ewe (NLW) was recorded as number of lambs present at weaning and ranged from one to six.

7.3.2 Data cleaning

Data were cleaned and traits were tested for normality as described in Chapter 5 to remove BCS records that were not whole or half scores between 0-5, ewes that had negative or zero RR values and one- and five-year-old ewes. Age of dam (AOD) was classified into three groups (1, 2 and 3+). Ewes were classified according to the following combinations of NLS and NLW; scanned and weaned single (1_1), scanned and weaned a twin (2_2), scanned a twin but weaned a single (2_1), scanned and weaned a triplet (3_3), scanned a triplet but weaned a twin (3_2) or a single (3_1). Age at first lambing (AFL) was determined based on whether the ewe had a first lambing date at one-year or two-years of age. For each ewe, average litter weaning weight (avWWT) and total litter weight weaned per ewe (TLW) was calculated from individual lamb weaning weight data.

7.3.3 Statistical Analysis

Descriptive statistics (Table 7.1) for the traits were obtained using the MEANS procedure of the statistical package SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

Variance components to obtain genetic parameters for BCS during the production season were obtained using ASReml version 4.0 (Gilmour et al. 2015) with a random regression model (RRM) over five BCS time points (event), these were mating (0 months), pregnancy scanning (3 months), prior to lambing (6 months), weaning (9 months) and the following mating (12 months). Contemporary group was defined as the group of ewes with a BCS measurement at the same year and event (YE). The data were analysed using the following RRM:

$$y_{ijlmodpt} = YE_j + BRR_l + \text{NLS-NLW}_m + AOD_o + AFL_d + PAR_p + \sum_{k=0}^{3} \beta_{kt} p_{kt} + \sum_{k=0}^{3} \alpha_{ki} p_{kt} + PEwithin_i + PEacross_i + e_{ijlmodpt}$$

where $y_{ijlmodpt}$ is the BCS of ewe i in month t; YE_j is a fixed effect of j contemporary group; BRR_l is a fixed effect of the l class of ewe birth-rearing-rank; NLS-NLW_m is a fixed effect of the m combination of NLS and NLW; AOD_o is a fixed effect of the o class of age of dam; AFL_d is a fixed effect of the d class of age at first lambing; PAR_p is a fixed effect of p of the class of parity. β_{kt} is the estimate of the k^{th} fixed regression coefficients of BCS in month t of the production year; α_{ki} are the k^{th} random regression coefficient for i^{th} animal; $PEwithin_i$ and $PEacross_i$ are for the permanent environmental effect of the i^{th} ewe within each parity and across all parities, respectively of the i^{th} ewe and $e_{ijlmodpt}$ is the residual error associated with observation $y_{ijlmodpt}$. The random residual errors were assumed to be homogenous across the months of measurement. p_{kt}'s are the Legendre polynomial coefficients, which are functions of month of measurement, calculated as

$p0(t) = 1$, $p_1(t) = x, p_2(t) = \frac{1}{2}(3x^2 - 1), p_3(t) = \frac{1}{2}(5x^3 - 3x)$, where $x = 2\left(\frac{t - t_{min}}{t_{max} - t_{min}}\right) - 1$ (Sivestre et al. 2009). In the current study $t_{min} = 0$ months and $t_{max} = 12$ months. The order of the random regression polynomials set were of third order which was determined based on the Akaike information criterion as the best model.

A matrix **C** of additive genetic (co)variances for each month of the production cycle were estimated using a covariance function from the following equations:

$$C = \phi\, G\, \phi'$$

where G is (co)variance matrix of the random regression coefficients for additive genetic effects and ϕ is the matrix of orthogonal polynomial coefficients.

7.3.4 Estimation of genetic parameters

Heritability (h^2) and repeatability (rep) for BCS at the t^{th} month were estimated as:

$$h_t^2 = \frac{\sigma_{at}^2}{\sigma_{at}^2 + \sigma_{pe}^2 + \sigma_c^2 + \sigma_e^2}$$

and

$$rep_t = \frac{\sigma_{at}^2 + \sigma_{pe}^2}{\sigma_{at}^2 + \sigma_{pe}^2 + \sigma_c^2 + \sigma_e^2}$$

Where σ_{at}^2 is the estimated additive genetic variance at month t, σ_{pe}^2 is the across all parities permanent environmental variance, σ_c^2 is the within parity permanent environmental variance and σ_e^2 is the residual error variance.

Ewe BCS change variance parameters were calculated from the random regression coefficients.

$$\mathrm{h}^2_{(\mathrm{X-Y})} = \frac{\sigma^2_{\mathrm{g}(\mathrm{X}-Y)}}{\sigma^2_{\mathrm{p}(\mathrm{X}-Y)}}$$

Where $\sigma^2_{\mathrm{g(X-Y)}} = \sigma^2_{\mathrm{g(X)}} + \sigma^2_{\mathrm{g(Y)}} - 2\sigma^2_{\mathrm{g(X,Y)}}$

And $\sigma^2_{\mathrm{p(X-Y)}} = \sigma^2_{\mathrm{p(X)}} + \sigma^2_{\mathrm{p(Y)}} - 2\sigma^2_{\mathrm{p(X,Y)}}$

Where $\sigma^2_{\mathrm{g(X-Y)}}$ is the genetic variance and $\sigma^2_{\mathrm{p(X-Y)}}$ is the phenotypic variance, between two BCS measurements.

7.4 Results

7.4.1 Descriptive Data

Means for the production traits and BCS change traits for each parity are presented in Table 7.1.

Table 7.1. Means (standard deviations in parentheses) for New Zealand Romney ewe body condition score (BCS), number of lambs scanned per ewe (NLS), number of lambs weaned per ewe (NLW), average litter weaning weight per ewe (avWWT), total litter weaning weight per ewe (TLW), and the change in BCS (ΔBCS) between mating and the following re-mating (mating to mating), over the first month of lactation (early lactation), over the lactation period (lactation) and weaning to re-mating (post-lactation).

Trait	Parity			
	1	2	3	4
n	806	1,990	1,070	437
average BCS	3.38 (0.27)	3.38 (0.26)	3.44 (0.27)	3.45 (0.27)
NLB	2.21 (0.62)	2.13 (0.7)	2.30 (0.68)	2.37 (0.71)
NLW	1.65 (0.75)	1.72 (0.76)	1.78 (0.79)	1.71 (0.88)
avWWT	33.02 (6.15)	35.02 (6.12)	36.55 (6.36)	36.51 (6.83)
TLW	54.14 (17.25)	61.07 (19.29)	66.68 (20.99)	64.95 (22.78)
ΔBCS mating to mating	-0.08 (0.22)	0.04 (0.20)	-0.03 (0.21)	-0.05 (0.2)
ΔBCS early lactation	-0.10 (0.05)	-0.08 (0.04)	-0.09 (0.04)	-0.09 (0.04)
ΔBCS lactation	-0.21 (0.1)	-0.16 (0.09)	-0.18 (0.09)	-0.19 (0.09)
ΔBCS post-lactation	0.28 (0.1)	0.26 (0.09)	0.25 (0.09)	0.25 (0.09)

7.4.2 Body condition score variances

Genetic and environmental variances were estimated over the production year (March to the following March Figure 7.1). The genetic variance was slightly greater than the permanent environmental variance. The residual variances were higher than both the genetic and permanent environmental variances. Variances were consistent through the central part of the production year (coinciding with pregnancy, 3-6 months) while values were slightly higher around mating (0 months). The mean heritability was 0.23 and mean repeatability was 0.42. The heritabilities of monthly BCS are presented in Figure 7.2.

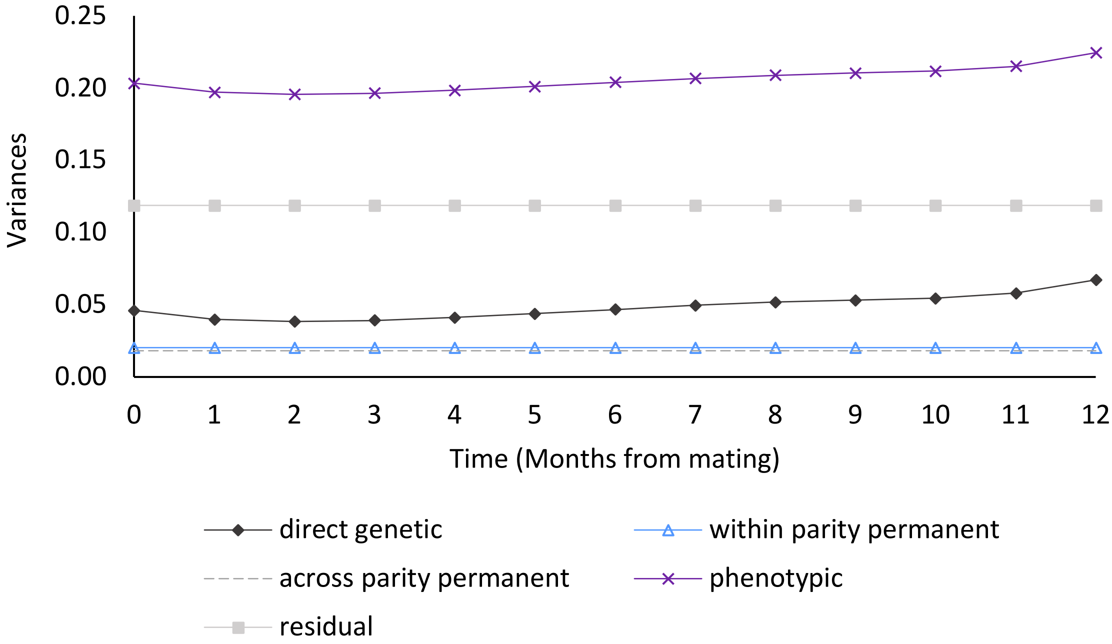

Figure 7.1. The monthly genetic, within and across parity permanent environment, residual and phenotypic variances for body condition score of New Zealand Romney ewes. Key time points included prior to mating (0 months from mating), at pregnancy scanning (3 months from mating), prior to lambing (6 months from mating), weaning (9 months from mating) and the following mating (12 months from mating).

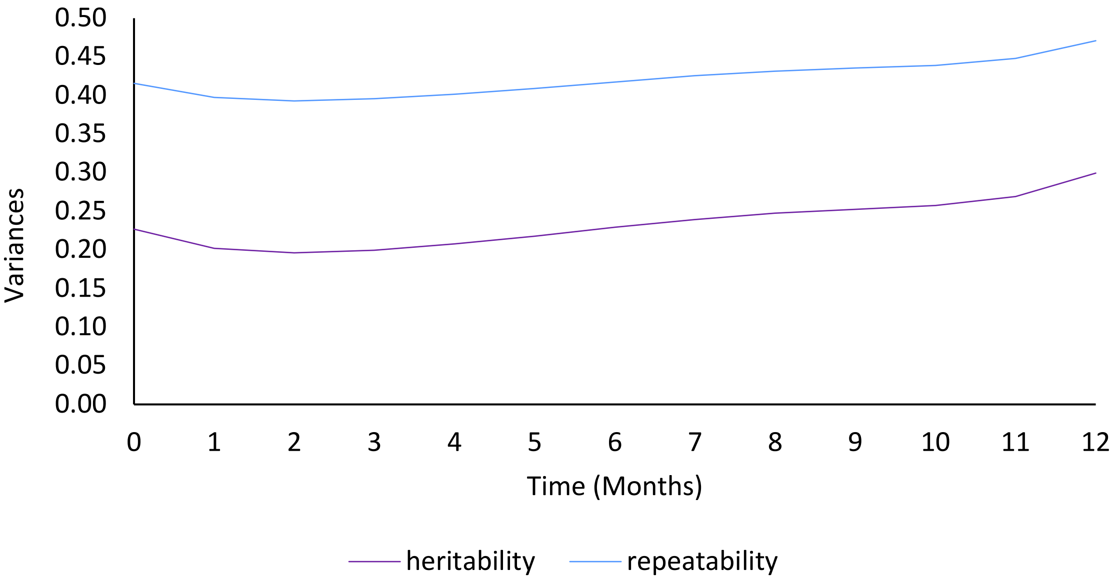

Figure 7.2. The monthly heritability (blue) and repeatability (purple) of body condition score of New Zealand Romney ewes.

The variance parameters for each time point across the production year were similar (Table 7.2). Phenotypic variance between time points was greatest between mating and the following mating (Month 0 to 12), from March to December (Month 0 to 9) and from March to July (Month 0 to 4). Heritabilities for BCS change across a production year were low.

Table 7.2. The genetic variance, residual variance and heritability of BCS change of New Zealand Romney ewes across a 12-month period between mating and the following re-mating (Month 0 to 12), from March to December (Month 0 to 9) from March to July (Month 0 to 4), from July to September (Month 4 to 6), from September to December (Month 6 to 9) and from December to March (Month 9 to 12)

BCS change	$\hat{\sigma}^2_{g(X)}$	$\hat{\sigma}^2_{g(Y)}$	$cov_{g(X,Y)}$	$\hat{\sigma}^2_{p(X)}$	$\hat{\sigma}^2_{p(Y)}$	$cov_{p(X,Y)}$	$\hat{\sigma}^2_{g(Y-X)}$	$\hat{\sigma}^2_{p(Y-X)}$	$\hat{h}^2_{X,Y}$
Month 0 to 12	0.05	0.07	0.05	0.21	0.23	0.09	0.02	0.26	0.08
Month 0 to 9	0.05	0.05	0.04	0.21	0.21	0.08	0.02	0.26	0.09
Month 0 to 4	0.05	0.04	0.03	0.21	0.20	0.08	0.02	0.26	0.06
Month 4 to 6	0.04	0.05	0.04	0.20	0.21	0.08	0.00	0.24	0.01
Month 6 to 9	0.05	0.05	0.05	0.20	0.21	0.09	0.00	0.24	0.00
Month 9 to 12	0.05	0.07	0.05	0.21	0.23	0.09	0.02	0.25	0.06

$\hat{\sigma}^2_{g(X)}$ = genetic variance of time X, $\hat{\sigma}^2_{g(Y)}$ = genetic variance of time Y, $cov_{g(X,Y)}$ = genetic covariance between time X and Y, $\hat{\sigma}^2_{p(X)}$ = phenotypic variance of time X, $\hat{\sigma}^2_{p(Y)}$ = phenotypic variance of time Y, $cov_{p(X,Y)}$ = phenotypic covariance between time X and Y, $\hat{\sigma}^2_{g(Y-X)}$= genetic variance of the change between time X and Y, $\hat{\sigma}^2_{p(Y-X)}$= phenotypic variance of the change between time X and Y, $\hat{h}^2_{X,Y}$ = heritability of the change between time X and Y.

7.5 Discussion

Ewe BCS profiles or curves have been previously investigated in sheep, but only in terms of describing the phenotypic profiles (Walkom et al. 2014a; Macé et al. 2019) and the genetic parameters of the change in BCS between each BCS measurement (Walkom and Brown 2017; Macé et al. 2018a; Macé et al. 2018b). Genetic BCS profiles have been examined in dairy cattle (see review by Roche et al. 2006), but not in a sheep population. The genetic BCS profiles may provide additional information that individual BCS measurements do not. In the current study the monthly BCS heritabilities were presented.

Mean BCS was greater than that reported previously by Shackell et al. (2011), 2.7-2.9 or Everett-Hincks and Cullen (2009) 3.07 at mid-pregnancy and 2.66 prior to lambing. Both used a similar population to that of the current study but included a larger number of sheep across more flocks. The study by Shackell et al. (2011) likely included records from the current study that were recorded in 2009. Mean avWWT in the current study of 33.0 kg to 36.6 kg was greater than that reported by Shackell et al. (2011) of 27.2 kg. The differences between these two studies may have resulted from genetic improvements made in production between the studies (Beef+Lamb New Zealand 2018) and/or differences in the feeding levels resulting in greater weights recorded for the Freestone flock in the current study.

7.5.1 Body condition score variances

The permanent environmental and within parity variance was lower than the genetic variance (Figure 7.1). The genetic variance displayed greatest variation around the mating period and was lowest around lactation. The residual variance was greater than both the genetic and permanent environmental variance. Together these results indicated that there were likely many factors influencing BCS throughout the production year that could not be accounted for due to lack of data. This was the first study of its kind to report sheep BCS variances across the production year. However, individual BCS measurement periods were comparable with the profiles of monthly variances seen in Chapter 5. The phenotypic variance of BCS in the current study was similar to that reported by Everett-Hincks and Cullen (2009) of 0.21 at mating and 0.18 prior to lambing. The variances for BCS presented in the current study indicate that there is a small change in genetic BCS throughout the year.

7.5.2 Heritability and repeatability estimates

This study appears to be the first to estimate heritability of sheep BCS across the production year (Figure 7.2). The data indicate that higher heritability estimates of BCS were obtained at the beginning and end of the production year and the lowest from mid-pregnancy to lambing (July to September). In this study, mating occurred in March and weaning in December. Previous New Zealand studies (Everett-Hincks and Cullen 2009; Shackell et al. 2011) and international studies (Borg et al. 2009; Mekkawy et al. 2009; Walkom et al. 2014b; Brown et al. 2017; Walkom and Brown 2017) have focused on a single BCS time point. Heritabilities for BCS across the year were similar to those reported previously in New Zealand studies reporting BCS at individual time points (Shackell et al. 2011). In the current study mean monthly heritability for all parities was 0.23 which was slightly less than that reported by Shackell et al. (2011) at mating and pregnancy scanning of 0.28 and 0.30, respectively. However, the mean monthly heritabilities in the present study were slightly greater than that reported by Everett-Hincks and Cullen (2009) at pregnancy scanning and lambing of 0.16 and 0.18, respectively. Therefore, among the heritabilities across the year were similar to those reported for New Zealand studies.

Previous studies have reported BCS repeatability as 0.12-0.41 (Everett-Hincks and Cullen 2009; Shackell et al. 2011; Walkom et al. 2014b; Brown et al. 2017; Walkom and Brown 2017). The repeatabilities in the current study were high (0.39 to 0.47), across the production year which are in agreement with the previous studies.

The RRM used, assumed homogeneous residual, within parity permanent environment and across parities permanent environment variances that potentially caused greater heritabilities across lactation due to the increased genetic variance, while the residual and permanent environment variances remained constant. The homogenous variances were not allowing for increases during pregnancy and lactation that would have resulted in a heritability similar to the mating heritability. As the genetic variance had a small range from 0.04 to 0.06, this would not have had a significant influence on the results reported in the current study. The small difference in BCS heritability across the production year indicates that a single BCS measurement could be included in the NZMW. Selection for BCS could be made on the mating BCS, however, whether the economic value of BCS remains linear or not needs to be assessed before it is included in the main NZMW index.

7.5.3 Heritability of BCS change

The current study was the first of its kind to consider the genetics of BCS across the production year. Phenotypic BCS at mating and weaning provides only a snapshot of the BCS of the ewe. Thus, looking at the BCS across the year may provide more information about the ewe and the fluctuations in BCS across the year. The heritability of BCS was greatest at mating which has been shown previously. However, the heritability of BCS change between time points has been reported as low (Walkom and Brown 2017; Macé et al. 2018a; Macé et al. 2018b). The benefit of using the RRM to predict BCS across the year allows for more specific time points to be investigated.

Heritabilities for BCS change across a 12-month period in the current study were low as a result of the variance parameters being similar for each time point across the production year. The genetic variance ranged 0.04 to 0.07 and the phenotypic variance ranged 0.20 to 0.23, therefore, the heritabilities were low. The genetic variance for the difference between time points ranged from 0.00 to 0.02, highlighting the low variation for genetic variances. The heritabilities were in agreement with previous studies and indicate that the ability to select for a certain BCS profile remain limited through selection for BCS change across a period of time.

7.6 Conclusions

This study was the first to show the heritability of BCS and BCS change throughout the production year in sheep. The estimated heritabilities of BCS in dual-purpose ewes were moderate across the production year and indicate that they could be used in a genetic evaluation for that population. The estimated heritabilities of BCS change were low indicating that the ability to select for ewe BCS profiles remain limited through genetic selection. The inclusion of BCS in the NZMW has some merit to improving ewe BCS, however, the economic importance of BCS in the current index requires further investigation.

8 General Discussion

8.1 Introduction

The ideal dual-purpose ewe is one that conceives within the first cycle (17 days) of breeding, produces multiple lambs every year, rears them all to weaning, at a heavy total litter weight, all while limiting adult ewe live weight increases (Sheep Improvement Limited 2019c). Any factor that impacts any of these traits will potentially decrease farm profitability.

It has been well established that individual ewe BCS influences their production (Kenyon et al. 2014), however, the mechanisms affecting production are less well understood. Body condition score profiles have been widely researched in dairy cattle (see review by Roche et al. 2009), showing that the amount of condition lost post-calving was associated with milk production and reproduction. There has been no similar research on BCS profiles across the production cycle for sheep in New Zealand and little conducted worldwide (Macé et al. 2018a; Macé et al. 2019). Typically, ewes in New Zealand have BCS that is lower than the industry targets (Casey et al. 2013), therefore, there is scope to improve production by increasing BCS.

Genetic selection is a strategy that could be used to increase the genetic potential of BCS, however, the genetic relationships between BCS and production traits have not been extensively researched in New Zealand (Everett-Hincks and Cullen 2009; Shackell et al. 2011). It is important to determine and understand the heritability of BCS and the genetic correlations between BCS and production traits such as number of lambs scanned (NLS), number of lambs weaned (NLW) and average litter weaning weight (avWWT) under New Zealand conditions to determine if including BCS in the maternal worth breeding objective would influence other important production traits.

The maternal worth breeding objective of the New Zealand sheep meat industry (NZMW) aims to improve the genetic ability of ewes to produce and rear two lambs to weaning and the lambs to be finished for slaughter (Sheep Improvement Limited 2019c). Currently there is a negative economic weighting on ewe live weight in the selection index with no account for BCS (Sheep Improvement Limited 2019c). Although there is a negative weighting on ewe live weight, the average weight of the national flock is increasing (Sheep Improvement Limited 2019a) in response to the high relative economic value placed on weaning weight (WWT). Live weight and WWT are highly genetically correlated (rg=0.54 - 0.73). The negative weighing on ewe live weight could potentially have ramifications due to the high genetic correlation between ewe live weight and BCS (Shackell et al. 2011) resulting in increasing BCS.

Currently, the sheep industry may be indirectly selecting for increased BCS, as the genetic trend of live weight maintains positive. Unlike live weight, BCS is an optimum trait where a BCS between 3.0 to 3.5 is desirable and low and high BCS values are undesirable (see review by Kenyon et al. 2014). Therefore, it is important that BCS is considered separately from adult live weight. The general aim of this thesis was to investigate the effects of genetic and phenotypic BCS and BCS change on ewe productive performance.

8.2 Summary of main findings

8.2.1 Phenotypic Body Condition Score

There was no additional benefit in exceeding a BCS of 3.5 at any point (ie mating, scanning, lambing or weaning) during the production year (Chapter 3), therefore, the current recommended industry target BCS of 3.0 to 3.5 (Kenyon and Cranston 2017) is still appropriate. This BCS target is in agreement with previous studies that have identified that BCS has a curvilinear relationship with pregnancy rate (Yilmaz et al. 2011; Corner-Thomas et al. 2015c), NLB (Atti et al. 2001; Abdel-Mageed 2009) and avWWT (Kenyon et al. 2012a; Kenyon et al. 2012b). In Chapter 3 there was no benefit to exceeding a BCS of 3.5, which is in agreement with the observation that BCS is an optimum trait where by low values result in reduced productive performance and high values have no increase in performance, but are likely to incur increased costs, or sometimes result in decreased performance (Rhind et al. 1984b; Sejian et al. 2009). An optimum BCS profile across the production year was reported in dairy cattle by Roche et al. (2009) for maximised milk production. Similarly, there is likely to be an optimum BCS profile for sheep.

In chapter 6, ewes were separated into clusters based on their BCS profile throughout the production year, from mating to the following mating. There were six different BCS profiles identified (Chapter 6) and sheep from these profiles displayed differing levels of performance. Five of the six BCS profiles were characterised by an average BCS decrease of 0.7 units from pregnancy scanning through to weaning followed by an increase in BCS from weaning to re-mating. Ewes that lost BCS between pregnancy scanning and weaning were associated with greater production, similar to that reported by Mathias-Davis et al. (2013) who reported that a negative BCS change between lambing and weaning was associated with greater lamb growth rates. Similarly, Mathias-Davis et al. (2011) showed that ewes with a high BCS at weaning had lower total litter weaning weight (TLW).

The loss in BCS between pregnancy scanning and weaning suggests that these ewes had mobilised their body reserves to produce milk. Lamb growth prior to weaning is associated with the ewe's milk production (Muir et al. 1999), therefore, a greater TLW exhibited among ewes that lost BCS from pregnancy scanning to weaning suggests greater milk production. There were increased estimated energy requirements associated with regaining BCS from weaning to the following mating (Chapter 6), that may potentially outweighed by the greater TLW exhibited by these ewes. Ewes that gain BCS between weaning and mating have been shown to have greater reproductive performance (see review by Kenyon et al. 2014), therefore, it is recommended that ewes are offered feed above requirements over this period.

Stayability was used as an indicator or proxy of survival rather than "true" survival because the final removal date (ie death, cull or sold) from the flocks was not recorded. The stayability of the ewe was lower among ewes that showed a one unit decrease in BCS from pregnancy scanning to weaning than ewes that decreased half of a BCS or maintained BCS. The impact that each different BCS profile had on ewe wastage would need to be investigated to determine the true influence of each BCS profile.

8.2.2 Phenotypic correlations between body condition score and production traits

There have been few studies that have reported the phenotypic correlation between BCS and reproduction in sheep (Brown et al. 2017; Walkom and Brown 2017), although, this has been extensively researched in dairy cattle (see review by Roche et al. 2009). From these reported studies in both dairy (Roche et al. 2009) and sheep (Brown et al. 2017; Walkom and Brown 2017) it would be expected that there is a negative phenotypic correlation between BCS and reproduction. The phenotypic correlation compares the linear relationship with each trait. Given that BCS is an optimum trait and as the ewes used in this thesis were largely within or close to the BCS range of 2.5 to 3.0, there was likely to be no greater production seen in ewes with greater BCS. Therefore as expected, the phenotypic relationships reported in the current study were low.

8.2.3 Heritability of body condition score

Both dual-purpose and fine wool breeds have been represented in this thesis because the breeding goals for both these sheep populations are vastly different. The New Zealand maternal worth (NZMW) is the index for dual-purpose breeds and includes lamb growth, adult size, reproduction, survival and wool (Chapter 2). The selection objectives for Merino focuses on fertility, wool and carcass traits (Meat & Livestock Australia Limited and Australian Wool Innovation 2009; New Zealand Merino 2018).

Heritability of BCS was estimated for Merino ewes at mating, scanning, lambing and weaning (Chapter 4), for Romney and Highlander ewes at mating and weaning (Chapter 5) and monthly across the production year in Romney ewes (Chapter 7). Estimated heritability of BCS for Merino (0.32-0.66) and dual-purpose (0.16-0.22), which were similar to previous studies (Everett-Hincks and Cullen 2009; Shackell et al. 2011; Walkom and Brown 2017). However, the heritability reported for Merino ewes was greater than published heritabilities for Australian Merino ewes of 0.08-0.11 reported by Walkom et al. (2014b) and 0.11 reported by Brown et al. (2017). There are numerous possible explanations for the high heritabilities in the Merino dataset studied, including low estimates of phenotypic variance, missing contemporary group records and sire and dam groups being unique to each birthyear cohort.

Overall, these heritabilities indicate that it would be possible to change the genetic potential for BCS with genetic selection. The addition of the modelled BCS profile across the production year showed that the genetic variation was similar across the year. Therefore, one BCS measurement per year will capture enough of the genetic variation to use for selection purposes (Chapter 7). The best time to measure BCS for selection of Merino or dual-purpose ewes is at mating as this had consistently the highest heritability and is a time of the year that is not complicated by the change in physical appearance due to pregnancy and lactation.

8.2.4 Heritability of body condition score change

Estimates of variance components and genetic parameters for BCS change were calculated to determine if some periods of change could be manipulated genetically to select for a desired BCS profile. The ewes with BCS profiles that lost phenotypic condition between scanning and weaning were identified as the most productive (Chapter 6). Whereas ewes that had a BCS profile that gained BCS post-weaning (Chapter 6) had greater BCS at mating. This greater BCS could then be used for energy to supplement pregnancy and lactation (Mathias-Davis et al. 2013).

The heritability for BCS change across the production year was low (0-0.08, Chapter 7), indicating that there would be minimal genetic progress made if BCS change was selected for. This is in agreement with previous studies such as Walkom and Brown (2017) who reported that the heritability of BCS change of 0.05 and Macé et al. (2018a) of 0.06-0.15.

8.2.5 Genetic correlations among body condition score measurements

Genetic correlations of BCS between measurement periods were estimated (mating, pregnancy scanning, lambing and weaning) across the production year. Moderate to high genetic correlations were found between measurement periods (0.39-0.83, Chapter 4 and 0.49-0.89, Chapter 5). These results are in agreement with previous studies (Everett-Hincks and Cullen 2009; Shackell et al. 2011; Walkom and Brown 2017). The moderate to high genetic correlations between BCS measurement periods indicate that genetic variance was similar for individual BCS measurements. This means that only one BCS per year is needed to be measured on-farm to capture majority of the genetic variation for BCS. As indicated above, it is recommended to measure mating BCS to achieve this.

8.2.6 Genetic correlations between body condition score and production traits

In the current studies there was a slight negative genetic correlation between BCS and NLS which aligns with previous reports (Brown et al. 2017; Walkom and Brown 2017), indicating that selection for increased BCS at mating could reduce ewe reproductive performance. However, reproductive performance is currently included in the NZ maternal worth (NZMW) index, so if BCS is not included in the index, BCS could decline. Therefore, the inclusion of BCS in the NZMW selection criterion should be investigated.

Among Merino sheep there was a moderately positive genetic correlation between BCS and fleece traits including yearling greasy fleece weight, fibre diameter, staple length, and staple strength (Chapter 4). These genetic correlations were in agreement with estimates reported by Walkom and Brown (2017) for Merino and Merino-cross ewes. Selection for increased BCS in Merino ewes would result in increased fleece weight, however, it would also increase fibre diameter. A finer fibre diameter achieves greater income for Merino ewes. Therefore, negative selection pressure on fibre diameter would also need to be implemented.

8.2.7 Genetic correlations between body condition score and live weight

Adult ewe Live weight and BCS were highly genetically correlated (Chapter 5). The current genetic trend for live weight is positive (Figure 8.1), even though there is a negative economic value placed on live weight (Sheep Improvement Limited 2019a). Therefore, BCS is likely to follow a similar trend to live weight, however, the positive genetic trend for BCS seems to only have started after around 2010 (Figure 8.2). The reason for the slight positive genetic trend for BCS from 2010 to 2019 is likely due to the high genetic correlation with live weight. In addition the number of sheep breeders actively recording BCS may have increased at this time, allowing more active management of ewes based on BCS. The increase in BCS measurements and management of ewes according to BCS may have resulted in increased culling due to low BCS, thus slightly increasing the BCS genetic trend even though it was not included in the selection objective.

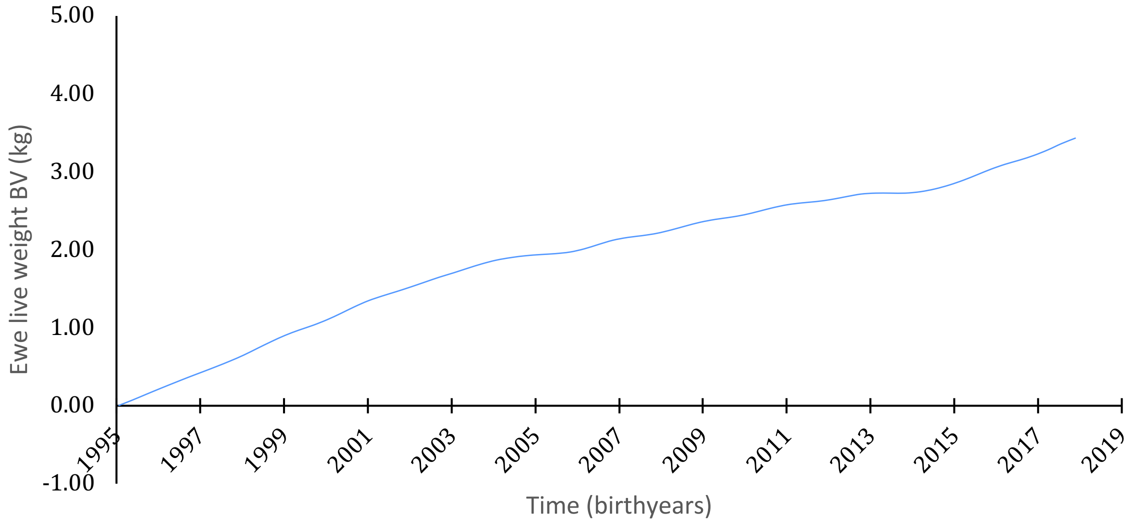

Figure 8.1. Trend in ewe live weight breeding value (BV) in New Zealand sheep (adapted from Sheep Improvement Limited 2019a, GE Analysis #36903 23/09/2019)

Accounting for BCS alongside live weight in the selection criterion would allow selection against low BCS and ensure that BCS does not exceed the optimal range of 3.0 to 3.5. To add BCS to the this selection index would require indices to be constructed using selection theory (Hazel 1943) to investigate different ways to include BCS in the NZMW selection index.

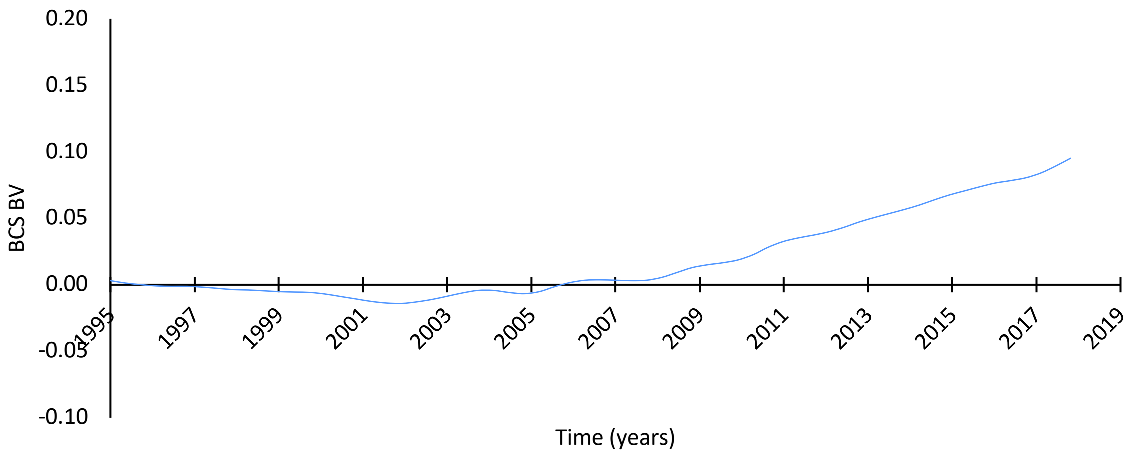

Figure 8.2. Trend in body condition score (BCS) breeding value (gBV) in New Zealand sheep (adapted from Sheep Improvement Limited 2019b, GE Analysis #36903 23/09/2019).

Although there were changes in production at different phenotypic profiles, there was low genetic variation indicating that this was not translated on a genetic level. These results indicated that feeding and environmental effects have the greatest influence on the production observed. It seems that the main purpose of maintaining ewe BCS between 3.0 and 3.5 at mating is to store of body fat reserves to allow energy to be used during pregnancy and lactation during periods of feed deficit as a result of limited pasture growth, quality and availability or restricted by rumen capacity. However, the results of this thesis show that BCS should be considered for the selection criterion to ensure it is balanced with the negative selection pressure placed on live weight. The inclusion of BCS into the NZMW selection objective is more complex than a simple linear selection, therefore, requiring further analysis of selection indices to determine the method of selection criteria for BCS.

8.3 Limitations

This thesis has shown that there are both phenotypic and genetic relationships between BCS, BCS change and productive performance in New Zealand sheep. The ewes used in this study were from a small number of flocks including; Merino ewes from the Merino central progeny test and dual-purpose nucleus flocks from Focus Genetics. It could be argued they were a convenience sample and not a randomly selected sample of New Zealand ewes. To achieve a randomly selected sample for genetic analysis would require a range of commercial farms to have pedigree recording along with BCS, live weight and production records. Such records are very costly and time consuming to collect, therefore, this approach is unrealistic when comparable results to other studies from pedigree data can be obtained as shown in this thesis.

The genetic parameters in this thesis were comparable to those reported for national (Everett-Hincks and Cullen 2009; Shackell et al. 2011), Australian (Brown and Swan 2014; Walkom et al. 2016; Brown et al. 2017; Walkom and Brown 2017), French (Macé et al. 2018a; Macé et al. 2018b) and North American (Borg et al. 2009) sheep populations. Therefore, it is likely that the genetic parameters for BCS reported in this thesis were similar to that which would be achieved in an ideal dataset (randomly selected sample).

The average BCS of the dual-purpose ewe population was at the industry BCS target of 3.5 (Kenyon and Cranston 2017). As many sheep farms in New Zealand do not actively measure and record BCS (Casey et al. 2013; Corner-Thomas et al. 2013), it is not known what the 'true' industry average would be, however, Casey et al. (2013) reported an average BCS of 2.36. The ewes in the current study were well above industry average. Therefore, there was potential bias in this dataset due to the average BCS being in the optimum range for production. To address this, future studies could utilise a pedigree recorded flock in New Zealand that operates at a lower average BCS. This would then provide data to determine if the same genetic and phenotypic correlations exist in a flock with a lower mean BCS and live weight.

The recording of final removal date (ie death, cull or sold) from the flocks was poor, therefore, stayability was used as a proxy for survival. Stayability to a three- and four-years-old was determined based on whether the ewe had the following mating BCS record. This stayability variable captured ewes that may have lost their lambs between lambing and weaning, but remained in the flock. Stayability has been reported to be a good measure of survival in sheep (McIntyre et al. 2012). The lower the stayability in a flock, the greater the number of replacement ewe lambs that need to be retained. Therefore, would have greater feed requirements for these unproductive young stock. As the flocks used in this thesis were nucleus breeding flocks, the stayability calculated for the flock used in Chapter 6 was likely to be above average due to there being more reasons to cull ewes. Nucleus breeding flocks often cull ewes at a young age based on breeding values as well as normal commercial culling based on traits such as barrenness, teeth, feet and udder conditions, low liveweight or low BCS. Future studies should include BCS data of ewes based on a commercial culling policy.

In the Merino and Freestone flocks BCS was recorded four times per year whereas the other three Focus flocks (Goudies, Pohuetai and Waipuna) measured BCS twice per year. For the purposes of genetic selection, more BCS measurements would not have added any more information than already presented in the current study. However, it would have added additional data points to increase the accuracy of prediction of the random regression models in Chapter 6 and 7. It is recommended for future BCS profile analysis to include additional BCS measurements to capture variation in BCS change throughout the year that is potentially missed with only recording four BCS measurements. These additional BCS measurements are recommended to be recorded across late-pregnancy and lactation, as this is the period where energy demands on the ewe are the greatest.

For accurate genetic parameters to be estimated there needs to be adequate number of records and pedigree. There were sufficient numbers and generations in the data for reliable genetic parameters to be estimated, however, the pedigree in the Merino population only recorded data of the ewes with a recorded sire thus, resulting in slightly overestimated heritabilities due to inflated genetic variances. Whereas, if there were data recorded for dams as well, this would have improved the linkage across years.

8.4 Future experiments to be considered

8.4.1 Optimum phenotypic body condition score profile

The BCS profiles presented in Chapter 6 show that ewes have different BCS profiles throughout the year. A loss in BCS between scanning and weaning was associated with increased TLW, however, the current study was conducted retrospectively. Therefore, the results presented were associations and not necessarily causation. It would be valuable to design a study to examine the effect of prospective phenotypic BCS profiles on production.

The design of the best experiment to assess both static and dynamic BCS in a nucleus flock is outlined below. The aim of this research would be to determine if feeding can be used to manipulate the BCS profile of the ewe to obtain similar levels of production as found in Chapter 6. The hypothesis would be that the treatment groups that differ in phenotypic BCS at weaning will have similar NLW, and therefore, similar production.

To test the effects of BCS profiles all ewes would have a BCS of 3.0 at mating and pregnancy scanning and the treatment groups would be balanced for live weight and litter size at pregnancy scanning. There would be three treatment groups to determine the effect of static BCS: Treatment A, ewes fed ad libitum with the aim of maintaining a BCS of 4.0. Treatment B ewes would be fed to maintain a BCS of 3.0 and Treatment C ewes would be fed to maintain a BCS of 2.0 throughout the production year. There would then be a further three treatment groups to determine the effect of dynamic BCS: Treatment D, ewes fed to their estimated feed requirements based on live weight and litter size with the aim of achieving a BCS profile similar to ewes in cluster 3 (BCS starts at 3.5, decreases to 3.0, Chapter 6). Treatment E ewes fed similar to commercial farming conditions that follow the pattern of feed supply for pasture with the aim of achieving a BCS profile similar to ewes in cluster 2 (BCS starts at 3.5, decreases to 2.5, Chapter 6). Treatment F ewes would start with a BCS of 3.5 and be fed to increase BCS to 4.0, achieving a BCS profile similar to ewes in cluster 5 (Chapter 6). Ewes would be followed until the following mating and measurements would include; BCS prior to lambing, early lactation BCS, BCS at docking, BCS at weaning, post-weaning BCS, BCS at re-mating, feed allocation, NLS, NLW, avWWT and costs associated with providing additional feed to maintain feeding levels for each treatment group.

The number of ewes required for this study would depend on how the litter size groups were allocated, whether that be grouped as singles and multiples or single, twins and triplets. For three litter size groups (single, twins and triplets) a sample size of 65 per treatment group would be required assuming the average avWWT is 26.7 kg, and that an acceptable difference in production between the treatments would be 10% (α=0.05, β=0.8). The objective of this study would be to determine the effect of both static and dynamic BCS on avWWT.

8.4.2 Genetic selection for optimal body condition score

The genetic analysis undertaken in both Chapter 4 and 5 reported genetic correlations between key production traits. The next step is to calculate selection indices to determine how BCS might be implemented in the selection index. The selection index for dual-purpose sheep is called the New Zealand Standard Maternal Worth Index (NZMW) and it was developed to represent how much a sheep is valued in cents above an average stud sheep in 1995. Selection indices are used as a predictor of a selection objective. There are many different potential selection indices which can represent a selection objective. To do this selection indices would need to be constructed using selection theory (Hazel 1943) to investigate different ways to include BCS in the NZMW selection index.

Selection indices consider the genetic and economic bases for various traits (Hazel 1943). The economic value for each trait depends on the amount of profit that may be expected to increase for each unit of improvement in that trait. To calculate selection indices, the traits already included in the current selection index would need to be included in a genetic analysis with BCS. Correlated responses to selection would need to be calculated using selection index theory. This would indicate the best combination of traits and economic weighting to include BCS into the selection index.

Body condition score is an optimum trait where a BCS between 3.0 to 3.5 is desirable and low and high BCS values are undesirable. As the current industry BCS is likely below optimum (Casey et al. 2013) and the genetic variance of BCS is low, there needs to be selection for increased BCS at mating. The base scenario would include selection on NZMW with the current economic values (Sheep Improvement Limited 2019a; Sheep Improvement Limited 2019c). Subsequent scenarios could include; linear BCS selection, BCS restricted to between 3.0 to 3.5 and equal genetic gains on each month of the BCS profile. Linear BCS selection only requires a single BCS trait.

When the BCS profile is optimal (maintains BCS between 3.0 and 3.5), the breeding objective is to increase production without changing the BCS profile.

8.5 General conclusions

The focus of this thesis was to explore ways BCS could be used to improve production through exploring the effects of genetic and phenotypic BCS and BCS change on productive performance. The results of the current study show that for dual-purpose ewes there was a phenotypic effect of BCS on production. There was no increase in production for ewes above a BCS of 3.5. BCS of 3.0 to 3.5 should remain the target BCS for phenotypic production.

The genetic correlations between BCS and production traits were low indicating that genetic selection for BCS will not likely influence genetics of production traits. The best time to record BCS for genetic selection was confirmed to be mating. Although there were changes in production at different phenotypic profiles, this was not translated on a genetic level, where the genetic correlations between BCS and production were low. The low genetic correlations between BCS and production indicate that feeding and environmental effects have the greatest influence on the production observed. Live weight and BCS are highly genetically correlated, therefore, it may be relevant to explore the inclusion of BCS in the selection objective to ensure that BCS does not exceed the optimal range of 3.0 to 3.5, although the development of the necessary selection indices was outside the scope of this thesis. Body condition score at mating is relevant to be included in selection as an optimum trait to ensure genetic progress is made with BCS.

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Appendices

Appendix One

8.5.1 Calculations for the estimated energy requirements used in Chapter 6.

The average cluster parameters are presented in Appendix Table 1. Maintenance requirements were calculated based on the average BCS across the BCS profile and converted into live weight (Morel et al. 2016) with the following equation.

$$\text{Live weight } = 7.27\text{BCS} + 38.46$$

Appendix Table 1. Average body condition score (BCS), liveweight, number of lambs scanned per ewe (NLS), average litter weaning weight per ewe (avWWT) and number of lambs weaned per ewe (NLW) for each cluster.

Cluster	BCS	Liveweight	NLS	avWWT	NLW
1	3.32	62.58	2.39	34.15	1.98
2	2.94	59.87	2.42	33.17	2.03
3	3.45	63.57	2.17	35.47	1.68
4	3.18	61.56	2.19	34.56	1.76
5	3.77	65.88	2.02	37.39	1.2
6	3.72	65.49	2.18	36.00	1.61

The total energy requirements (Appendix Table 2) were the sum of the maintenance, pregnancy, lactation and BCS change requirements (Nicol and Brookes 2007). Feed requirement per lamb was calculated as the total feed requirement divided by NLW (Appendix Table 2).

Appendix Table 2. The energy requirements (MJME) for maintenance, pregnancy, lactation, body condition score (BCS) gain and the estimated total energy (TE) requirements (MJME) and energy per lamb (MJME).

Cluster	Maintenance	Pregnancy	Lactation	BCS Gain	TE	Energy Per lamb
1	4223	478.7	3223	23.8	7906.4	127.52
2	4805	483.5	3296	80.8	7892.0	125.35
3	4273	433.2	2735	76.0	6931.7	137.64
4	4171	438.0	2863	115.0	6994.4	136.86
5	4389	404.2	1945	100.0	6762.2	153.01
6	4369	436.5	2624	13.9	6512.8	136.29

Appendix Two

Statements of contribution to doctoral thesis containing publications for chapters 3 and 4.

MASSEY UNIVERSITY
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UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Isabel Vialoux
Name/title of Primary Supervisor:	Associate Professor Rebecca Hickson
In which chapter is the manuscript /published work: 3	

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Tait IM, Kenyon PR, Garrick DJ, Lopez-Villalobos N, Pleasants AB, Hickson RE. 2019. Associations of body condition score and change in body condition score with lamb production in New Zealand Romney ewes. New Zealand Journal of Animal Science and Production 79: 91-94.

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:
- The percentage of the manuscript/published work that was contributed by the candidate:
- Describe the contribution that the candidate has made to the manuscript/published work:

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Isabel Vialoux Digitally signed by Isabel Vialoux Date: 2020.07.13 11:39:21 +12'00'
Date:	13-Jul-2020
Primary Supervisor's Signature:	Rebecca Hickson Digitally signed by Rebecca Hickson Date: 2020.07.13 11:42:02 +12'00'
Date:	13-Jul-2020

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Isabel Vialoux
Name/title of Primary Supervisor:	Associate Professor Rebecca Hickson
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Tait IM, Kenyon PR, Garrick DJ, Pleasants AB, Hickson RE. 2018. Genetic and phenotypic correlations between production traits and adult body condition scores in New Zealand merino ewes. New Zealand Journal of Animal Science and Production 78: 71-75.

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- The name of the journal:
- The percentage of the manuscript/published work that was contributed by the candidate:
- Describe the contribution that the candidate has made to the manuscript/published work:

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Isabel Vialoux Digitally signed by Isabel Vialoux Date: 2020.07.13 11:36:35 +12'00'
Date:	13-Jul-2020
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Date:	13-Jul-2020

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.