Investigating the relationship between lamb weaning age and forage diet on carcass and meat quality

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Abstract

Lamb carcass characteristics and meat quality are important components of the value chain that determine the carcass value and price obtained. On-farm factors can affect carcass characteristics and meat quality of lamb, however, the effect of early weaning and forage diet on carcass and meat quality characteristics is not well-known. Therefore, this thesis considers the relationship between weaning age and the forage diet for influencing carcass characteristics and meat quality of lamb.

The study compared carcass characteristics and meat quality of early weaned lambs (at eight weeks of age) grazing a plantain-clover mix, and conventionally weaned lambs (at 14 weeks of age) grazing a plantain-clover mix or perennial ryegrass-white clover pasture with all lambs finished for six weeks as one mob on perennial ryegrass-white clover pasture to achieve a target minimum live weight of 35 kg at slaughter (Chapter 3). Forty-three Romney ewes rearing twin lambs (86 lambs) were used in this study. Ewes and their lambs were allocated to one of four treatments: 1) lambs weaned early (eight weeks of age) on a plantain-clover mix (EARLY), 2) lambs with dam grazing a plantain-clover mix (HERB), 3) lambs with dam grazing perennial ryegrass-white clover pasture >1200 kgDM/ha (HIGH), and 4) lambs with dam grazing perennial ryegrass-white clover pasture <1200 kgDM/ha (LOW). Lambs in treatments 2, 3, and 4 were weaned at 14 weeks of age.

Lambs in the HERB treatment had the fastest growth rate, yielding heavier carcasses and a higher dressing out percentage compared to EARLY and LOW lambs. HIGH lambs had intermediate growth rates, carcass weights and dressing out % (Chapter 5, Table 8). Physical dissection of the hind leg showed lambs in the EARLY treatment had the least dissectible fat compared to HIGH and LOW lambs which had the most, with HERB lambs intermediate. In addition, lambs in the EARLY treatment had a similar fat% and muscle% compared to HERB and LOW lambs but produced lower fat% and higher muscle % than lambs in the HIGH treatment (Chapter 5, Table 9).

Objective measurements of lamb meat quality only showed a difference among treatments for sarcomere length and total shear force work (Chapter 5, Table 10). Lambs in the EARLY and HIGH treatments had the longest sarcomere lengths and lambs in the HERB treatment the shortest, with intermediate lengths recorded for LOW lambs. Meat from lambs in the EARLY, HERB and LOW treatments required less total shear force work than lambs in the HIGH treatment. Although statistically significant the relative difference in results was not substantial, indicating that generally the treatments had no effect on meat quality.

Early weaning of lambs onto a plantain-clover mix does not have negative effects on carcass and meat quality. However, the slower growth rate of early weaned and restricted perennial ryegrass pasture raised lambs resulted in lower carcass weights in this study indicating that a lower nutritive

diet as a consequence of using grass species or a lack of milk intake will mean lambs will need more time to achieve a set finishing weight.

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Chapter 1: Introduction

In New Zealand, sheep-production systems are mainly pasture-based, consisting of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) (Kemp *et al.*, 2002). Lambs are born late winter/early spring to coincide with peak pasture production and weaned at 10-14 weeks of age (Geenty, 2010). Lamb growth during the early lactation period depends on both the quantity and quality of milk and pasture consumed, and the efficiency of utilisation of the absorbed nutrients (Cranston *et al.*, 2016). Ewe milk production peaks in the first week of lactation producing 2400 g/day with lower quantities produced after week eight of lactation, 1200 g/day (Peterson *et al.*, 2006b). Lambs increase grazing time and consume less milk as lactation proceeds, where 20-day old lambs spend 20% of the day grazing compared to 56-day old lambs grazing 35% of the day (Peterson *et al.*, 2006a). Therefore, after eight weeks of age lambs predominantly graze pasture, effectively becoming competitors with the dam. Feed competition can decrease lamb growth prior to weaning and lengthen the time to reach slaughter weight (Rattray *et al.*, 1982). Conventional weaning, at approximately 14 weeks, can also delay ewes regaining body condition prior to mating partly because lambs suckle for a longer period and the lactation requirement diverts nutrients away from body condition gain (Cranston *et al.*, 2016). Alternatively, early weaning at eight weeks of age (onto a high nutritive crop) prioritises nutrition for the lamb improving growth and growth efficiency (Cranston *et al.*, 2016, Brown, 1964). Early weaning can be associated with nutritional stress or behaviour constraints which may limit total energy intake, reduce growth rate and mobilise fat stores (altering carcass composition) resulting in lighter carcasses at slaughter (Geenty, 1980) and potentially negatively affecting carcass and meat quality characteristics.

Plantain (*Plantago lanceolata*) has a greater feeding value than perennial ryegrass pasture. Leafy plantain has a higher dry matter digestibility and metabolisable energy value, allowing for a higher voluntary feed intake and nutritive value compared to perennial ryegrass pasture (Kemp *et al.*, 2010). A plantain-clover mix can be utilised to provide targeted nutrition for priority stock classes, enabling weaned lambs to grow faster compared to lambs grazing perennial ryegrass pasture, optimising lamb live weight gain for timely finishing during spring, summer, and autumn (Somasiri *et al.*, 2016, Somasiri *et al.*, 2015a, Somasiri *et al.*, 2015b). Herb-mixes have also been utilised for early weaning while still achieving suitable lamb growth rates (Ekanayake *et al.*, 2018).

On-farm factors affecting meat quality can include age and weight at slaughter, and the diet provided (Sañudo *et al.*, 1998a). The forage diet provided can influence key traits such as ultimate pH (Campbell *et al.*, 2011) and tenderness (Schreurs *et al.*, 2013). The diet may act directly on meat quality characteristics but is more likely to act indirectly through differences in carcass characteristics as a consequence of age and liveweight at slaughter (Purchas, 1989).

New Zealand lamb production is seasonal and price for lamb fluctuates across the season (traditionally declining after Christmas). Weaning lambs at eight weeks of age onto a high nutritive forage can help ensure lambs are finished and sold at premium export prices (Speijers *et al.*, 2004). Grazing lambs on a plantain-clover mix during spring and early summer can improve lamb performance and reduce the time to slaughter, increasing farm efficiency and gross margins (Speijers *et al.*, 2004).

The study aims to investigate if weaning lambs at eight weeks of age compared to 14 weeks of age has an influence on carcass and meat quality, and determine if there is a difference in carcass and meat quality of lambs grown on a plantain-clover mix compared to a perennial ryegrass-white clover pasture.

Chapter 2: Literature Review

2.1 Effect of forage diets on lamb growth

In New Zealand some sheep production systems experience dry conditions during summer and autumn which reduces perennial ryegrass pasture quality and production (Charlton and Stewart, 1999) which limit animal growth performance (Golding *et al.*, 2011). Growth performance can be manipulated through the quantity and quality of feed provided, defined by management options and seasonal conditions (Perry and Thompson, 2005). Forage herbs, such as plantain, have a taproot allowing access to water that is deeper in the soil profile which increases crop yield and dry matter (DM) availability into the summer (Kemp et al., 2010). Using a herb-legume mix such as plantain-clover (consisting of plantain, white clover and red clover) provides additive benefits from all the species as the growing season is prolonged (Kemp *et al.*, 2010). Thus, a plantain-clover mix can provide flexibility in sheep production systems by acting as a supplementary or finishing forage during spring, summer, and autumn (Golding *et al.*, 2011). A plantain-clover mix can increase the total dry matter on offer and subsequently voluntary intake (Speijers *et al.*, 2004) to improve lamb growth rate by up to 70% (Kemp *et al.*, 2010), yielding heavier lambs at slaughter with superior carcass characteristics.

Lamb performance on perennial ryegrass pasture averages at 128 g/day (Table 1) which is within the range 80-150 g/day reported in the review of Kemp *et al.* (2010). In comparison, mean lamb live weight gain on a plantain-clover mix tend to be greater, 239 g/day (Cranston *et al.* (2018), Somasiri *et al.* (2015a), Schreurs *et al.* (2013); Table 1), which is similar to the growth rate of 250 g/day reported in the review of Kemp *et al.* (2010). When comparing across studies, lambs grow 46 g/day faster when grazing plantain-clover compared to perennial ryegrass-white clover pasture (Table 1). Therefore, lambs grazing plantain-clover should reach set slaughter weight faster than lambs grazing perennial ryegrass-white clover pasture. Plantain-clover swards have the potential to rear faster growing lambs which provide farmers with several advantages; namely, a greater proportion of the total feed requirement contributes to growth rather than maintenance which increases farm efficiency (Rattray *et al.*, 1976), less time taken for lambs to be finished for sale and increase the number of lambs finished per unit DM/ha (Golding *et al.*, 2011).

The absence of clover in a pasture or a forage mix lowers the feeding value of the sward and subsequently reduces the relative growth rate of grazing lambs (Cranston *et al.*, 2018). This can explain the low lamb growth rates seen in pure plantain and perennial ryegrass swards compared to a plantain-clover mix or herb-legume mix, consisting of plantain, chicory, white clover, and red clover (Table 1). Utilising a herb-legume mix, such as plantain-clover, that have a higher nutritive value compared to perennial ryegrass-white clover pasture can increase the quantity and quality of feed on offer and subsequently improve lamb growth performance.

Table 1 Lamb growth performance (g/day), post-weaning, when grazing perennial ryegrass pasture (perennial ryegrass and white clover; Rye/WC) or a plantain-clover mix (plantain, white clover and red clover; Plantain/C) during late spring (November), summer (December to February), and autumn (March to May).

Study	**Finishing period (days)**	**Age at slaughter (months)**	**Live Weight Gain (g/day)**	
			Plantain/C	Rye/WC
Late spring				
Cranston et al. (2018)				
2016	50	7	199[a]	152[b]
2017	42	6.5	282[a]	141[b]
Somasiri et al. (2016)				
2011	47	5.5	305[a]	190[b]
2012	47	5.5	316[a]	244[b]
Summer				
Somasiri et al. (2015a)				
2012	48	5	226[a]	169[b]
2013	25	5	231[a]	120[b]
Kemp et al. (2014)*				
2009	45	7.5	219	-
2010	44	7.5	109	-
Campbell et al. (2011)*				
2008	42	6	110	150
Fraser and Rowarth (1996)*				
1993	-	-	141[a]	128[b]
1994	-	-	84[b]	98[a]
1995	-	-	102[b]	136[a]
Deaker (1994)*				
1993	82	6.5	143	135
Autumn				
Somasiri et al. (2015b)				
2012	35	7	295[a]	160[b]
2013	43	8.5	252[a]	170[b]
Schreurs et al. (2013)				
2012	35	7	259[a]	161[b]
Golding et al. (2011)#				
2007	50	7	247	119
2008	28	7	246	56
Average	**44**	**6.6**	**192**	**146**

*: lambs grazed pure swards of plantain and perennial ryegrass pasture
#: lambs grazed a herb mix of plantain, chicory, white clover and red clover or perennial ryegrass-white clover pasture
[a, b] superscripts that are different indicate means are significantly different ($P < 0.05$) within each study

2.2 Influence of lamb weaning age on growth performance after weaning

Weaning lambs early, between three to five weeks of age, can reduce lamb survival (Rattray *et al.*, 1976) and growth rate (Geenty, 1979, Rattray *et al.*, 1976). Growth checks occur because the rumen is undeveloped and the lambs are physically incapable of obtaining nutrients from a solid feed source at such a young age (Brown, 1964). Growth checks reduce the daily liveweight gain, mobilise fat stores reducing carcass fatness, and increase the time taken to reach slaughter weight and potentially result in lighter carcasses at slaughter with lower dressing out percentage, DO% (Ekiz *et al.*, 2012). Rumen development in lambs occur between four to eight weeks of age and the rate of development depends on the quality and quantity of forage provided (Rattray *et al.*, 1976). The reticulo-rumen comprises 2.7%, 4.4%, and 7.5% of lamb live weight for lambs weaned at four, six, and eight weeks of age, which shows rumen development increases as the lamb gets older and starts to consume more forage (Rattray *et al.*, 1976). At eight weeks of age the rumen of lambs are sufficiently developed to ferment herbage and weaning at this age has had minimal negative effects on lamb growth and live weight post-weaning (Munro and Geenty, 1983, Rattray *et al.*, 1976). To mitigate the negative effects of early weaning, ensuring a good growth rate to weaning and also providing a high nutritive forage from weaning until slaughter will improve average daily gain and limit fat loss whilst maximising the liveweight reached during the finishing period (Sañudo *et al.*, 1998b).

2.3 Effect of forage diets for lambs on carcass characteristics

2.3.1 Carcass weight

New Zealand lamb production systems have an emphasis on producing carcasses attributed with a high meat yield to achieve premium schedule prices and maximise return (Golding *et al.*, 2011, Judson *et al.*, 2009). Research has shown lambs finished on a high nutritive forage, such as chicory (Deaker, 1994), lucerne (De Brito *et al.*, 2016), brassica (Campbell *et al.*, 2011), red clover (Speijers *et al.*, 2004) or white clover (Deaker, 1994) yield a heavier carcass with a higher DO% compared to lambs grazing perennial ryegrass pasture. Likewise, this can be seen when comparing lambs finished on a plantain-clover mix vs perennial ryegrass-white clover pasture, on average, lambs finished on plantain-clover produce a 1.4 kg heavier carcass with a dressing percentage that is 2.6% higher (Table 2). In comparison, lambs grazing pure plantain or perennial ryegrass swards produce similar carcass characteristics, i.e. hot carcass weight, LMY%, and GR (Campbell *et al.* (2011); Table 2). Combining white clover and red clover with plantain increases the feeding value compared to plantain alone and the plantain-clover sward will produce more liveweight gain per kgDM (Somasiri *et al.*, 2015a). The nutrient composition of mixed herb and clover diets allows for an indirect effect on carcass characteristics through lamb growth rate, increasing carcass weight and the level of fatness (Schreurs *et al.*, 2013).

2.3.2 Carcass composition

Live weight of a lamb increases when they are fed above their maintenance energy requirement which leads to an increase in carcass weight. Protein retention for muscle development is optimal when lambs are fed *ad libitum* with a moderate protein diet containing 17.5 g of crude protein/kg DM, furthermore, this feeding level exceeds the maintenance energy requirement which also allows for fat deposition (Andrews and Ørskov, 1970). Kirton *et al.* (1981) compared two different feeding levels, *ad libitum* vs restricted fed perennial ryegrass pasture, and noted lambs from the former treatment produced heavier fatter carcasses compared to lambs from the latter treatment.

In New Zealand, lambs are sent for slaughter at a minimum of 35 kg liveweight. A change in carcass weight is associated with a change in carcass composition (Kirton *et al.*, 1981). If carcass weights at slaughter are similar due to sending lambs for processing at a target live weight it could be expected that carcass characteristics such as LMY% will not differ regardless of the forage grazed, as seen in Wong *et al.* (2018) and Campbell *et al.* (2011) (Table 2). Lambs grazing a plantain-clover mix have produced carcasses with a greater soft tissue depth (GR) by 2.9 mm compared to carcasses from lambs grazing perennial ryegrass-white clover pasture when comparing over multiple studies (Table 2). If animals are grown to the same slaughter weight, carcass characteristics generally do not differ regardless of the type of feed being grazed because animals are slaughtered at a set weight with only the time or age taken to get to slaughter differing (Speijers *et al.* (2004); Table 2). Therefore, New Zealand sheep farmers can benefit from slaughtering lambs at a set weight to ensure lamb carcasses reach a medium to heavy weight and are graded as prime to achieve premium market prices.

Table 2 Carcass characteristics of lambs grazing perennial ryegrass pasture (perennial ryegrass and white clover; Rye/WC) or a plantain-clover mix (plantain, white clover and red clover; Plantain/C) during late spring (November), summer (December to February), and autumn (March to May).

Study	Finishing period (days)	Age at slaughter (months)	Carcass weight (kg)		DO%[1]		LMY% (VIAscan)[2]		GR (mm)[3]	
			Plantain/C	Rye/WC	Plantain/C	Rye/WC	Plantain/C	Rye/WC	Plantain/C	Rye/WC
Wong *et al.* (2018)[#]	56	4.5	17.4	16.7	42.7	41.6	54.2	54.3	8.2[a]	6.6[b]
Somasiri *et al.* (2016)										
2011	47	5.5	18.3[a]	15.7[b]	41.4[a]	39.4[b]	-	-	7.9[a]	3.4[b]
2012	47	5.5	19.3[a]	17.1[b]	41.8[a]	40.1[b]	-	-	7.7[a]	5.6[b]
Somasiri *et al.* (2015a)										
2012	48	5	18.7[a]	15.7[b]	42.5[a]	38.0[b]	-	-	8.0[a]	4.9[b]
2013	25	5	16.8[a]	14.5[b]	40.3[a]	37.5[b]	-	-	6.1[a]	3.5[b]
Somasiri *et al.* (2015b)										
2012	35	7	18.6[a]	15.2[b]	41.8[a]	38.0[b]	-	-	8.4[a]	3.8[b]
2013	43	8.5	18.6[a]	16.7[b]	41.4[a]	40.4[a]	-	-	10.2[a]	7.3[b]
Kemp *et al.* (2014)[*]										
2009	45	7.5	17.9	-	44.7	-	-	-	-	-
2010	44	7.5	15.4	-	40.7	-	-	-	-	-
Schreurs *et al.* (2013)										
2012	35	7	18.8[a]	15.2[b]	-	-	-	-	8.1[a]	3.9[b]
Campbell *et al.* (2011)[*]										
2008	42	6	15.2	15.6	-	-	58.3	59.1	-	-
Golding *et al.* (2011)[#]										
2008	28	7	15.7[a]	14.8[b]	41.8[a]	38.8[b]	-	-	4.2[a]	3.4[b]
Fraser and Rowarth (1996)[*]										
1993	-	-	16.8[a]	15.6[b]	-	-	-	-	-	-
1994	-	-	14.1	14.6	-	-	-	-	-	-
1995	-	-	17.1[b]	18.4[a]	-	-	-	-	-	-
Deaker (1994)[*]										
1993	82	6.5	16.8[a]	15.6[b]	47.9[a]	45.1[a]	-	-	-	-
Average	**44**	**6.3**	**17.2**	**15.8**	**42.5**	**39.9**	**56.3**	**56.7**	**7.6**	**4.7**

1. DO%: dressing out percentage
2. LMY%: lean meat yield percentage
3. GR: soft tissue depth over the 12th rib 11 cm from the midline

*: lambs grazed pure swards of plantain and perennial ryegrass pasture

#: lambs grazed a herb mix of plantain, chicory, white clover and red clover or perennial ryegrass-white clover pasture

[a, b] superscripts that are different indicate means are significantly different ($P < 0.05$) within each study

2.4 Effect of lamb weaning age on carcass characteristics

2.4.1 Carcass weight and dressing out (DO%)

The effects of early weaning on lamb growth and live weight at slaughter vary. Early weaning, at six to eight weeks of age, for lambs reared by mature (Geenty, 1979, Furnival and Corbett, 1976, Rattray *et al.*, 1976) or yearling (Mulvaney *et al.*, 2011, Mulvaney *et al.*, 2009) ewes did not affect lamb live weight at slaughter.

In general, early weaned lambs produce lighter carcasses with a lower DO% compared to conventional weaned lambs and lambs slaughtered directly at weaning (Table 3). Purchas (1979) noted that lambs slaughtered directly off the dam (at 14 weeks of age) grew 36 g/day faster, yielding carcasses 600 g heavier and had a DO% that was 1.9 % greater compared to lambs weaned at nine weeks of age and slaughtered at the same age. Lambs slaughtered directly off their dam (at 11 weeks of age) consume low quantities of forage which result in an undeveloped rumen and lower digestive tract content which can partly explain the higher DO% sometimes observed for these lambs compared to lambs weaned at six and nine weeks of age and slaughtered at the same age (Cañeque *et al.*, 2001). Therefore, farmers that wean lambs early at six weeks of age (Rattray *et al.*, 1976) can expect carcasses with a lower DO% compared to lambs weaned between 8 to 15 weeks of age (Geenty, 1979, Rattray *et al.*, 1976) and lambs slaughtered directly at weaning (Cañeque *et al.*, 2001).

Other studies have investigated weaning age and the effect on carcass and meat quality characteristics by rearing lambs with their dam in pens indoors and feeding lucerne hay and concentrate (Ekiz *et al.*, 2012) or cereal straw and concentrate (Sañudo *et al.*, 1998b), compared to lambs with their dam on a grass based pasture supplemented with lucerne hay and concentrate (Cañeque *et al.* (2001); Table 3). Indoor lambs produce a lighter carcass, higher DO%, lower soft tissue depth and greater composition values compared to lambs mainly grazing herbage at foot. Published studies have shown the effect of weaning age on carcass weight, DO%, and carcass composition (Table 3 and 4) of lambs at foot which decreases with age with little effect seen after eight weeks of age, but few studies have considered the effect of weaning age and forage diet on carcass composition.

Table 3 The effect of different weaning ages on hot carcass weight and dressing out percentage of lamb carcasses.

Trait/Study	Diet[1]	Weaning Age			Slaughter Age
		Early wean (5 to 8 weeks)	Conventional wean (9 to 11 weeks)	Not weaned	
Hot carcass weight (kg)					
Ekiz *et al.* (2012)	S	10.6[a]	11.2[a]	13.6[b]	17 weeks
Cañeque *et al.* (2001)	P + S	12.1[a]	12.2[a]	13.0[b]	11 weeks
Sañudo *et al.* (1998b)	S	10.4[a]	-	11.2[b]	14 weeks
Earl *et al.* (1990)	P	14.5	14.6	15.3	29 weeks
Munro and Geenty (1983)	P	12.6	-	-	18 weeks
Geenty (1979)	$P_{pre} + L_{post}$	12.4[b]	15.6[a]	16.1[a]	15 weeks
Average	**-**	**12.1**	**13.4**	**13.8**	**17.3 weeks**
Dressing Out %					
Ekiz *et al.* (2012)	S	53.5[a]	54.6[a]	56.0[b]	17 weeks
Cañeque *et al.* (2001)	P + S	57.6[a]	58.6[b]	59.1[c]	11 weeks
Sañudo *et al.* (1998b)	S	49.7[a]	-	52.2[b]	14 weeks
Earl *et al.* (1990)	P	42.0	43.0	45.0	29 weeks
Munro and Geenty (1983)	P	45.9	-	-	18 weeks
Geenty (1979)	$P_{pre} + L_{post}$	46.0[b]	47.0[a]	50.0[a]	15 weeks
Rattray *et al.* (1976)	P	47.9[b]	50.2[a]	-	12 weeks
Average	**-**	**48.9**	**50.7**	**52.5**	**16.6 weeks**

1. Diet: P = grass-based pasture, S = supplemented lucerne hay and concentrate, $P_{pre} + L_{post}$ = grass-based pasture pre-weaning and lucerne post-weaning

[a, b, c] superscripts that are different indicate means are significantly different (P < 0.05) within each study

2.4.2 Carcass composition

2.4.2.1 Muscle and bone

Muscularity can be defined as 'the thickness of muscle relative to a skeletal dimension' (De Boer *et al.*, 1974). An increase in muscularity is associated with a heavier carcass (Hopkins, 1996), high M:B, greater lean meat yield, and lower carcass fat levels (Jones *et al.*, 2002). Muscle% does not differ between lambs weaned at eight or 14 weeks of age and slaughtered at 20 weeks of age (Wong *et al.*, 2018); however, lambs slaughtered directly at weaning have a lower muscle% compared to lambs weaned at six and nine weeks of age (Cañeque *et al.* (2001); Table 4). In comparison, Purchas (1979) recorded no difference in muscling between lambs weaned at nine weeks of age and lambs slaughtered directly at weaning. There is no difference in bone% between early weaned, conventional weaned and lambs still with their dam (Table 4). Similarly, Sañudo *et al.* (1998b) recorded no effect of weaning age on bone% of the shoulder between lambs slaughtered directly at weaning (at 14 weeks of age) and lambs weaned early (at six weeks of age) and slaughtered at the same age. Given lambs are slaughtered a target liveweight little to no variation in muscle and bone composition can be expected.

2.4.2.2 Fat

Carcass fatness of lambs tend to increase when the suckling period is lengthened (Cañeque *et al.*, 2001). Milk promotes fat deposition because it is utilised more efficiently by the lamb compared to grass-based pasture (Sañudo et al., 1998). The higher fat content of lambs slaughtered directly at weaning compared to early and conventional weaned lambs can be attributed to a higher energy intake of sucking lambs (Cañeque *et al.*, 2001). Weaning can cause nutritional stress which results in mobilisation of body fat; however, the extent of fat mobilisation decreases as the weaning weight and age increases (Geenty, 1980). Weaning lambs at four weeks of age can decrease carcass fat by 2-5% compared to weaning lambs at six and 18 weeks of age (Geenty, 1980).

Plasma non-esterified fatty acid (NEFA) levels in lambs weaned at 3.5 weeks of age were elevated for up to three weeks post-weaning, indicating fat mobilisation, compared to lambs weaned at 5.5 weeks of age which only showed elevated levels for two days post-weaning. Furthermore, lambs weaned at 7.5 and 9.5 weeks had similar plasma NEFA concentrations post-weaning (Fennessy *et al.*, 1972). Similarly, Jagusch *et al.* (1971) noted that weaning at 3.5 and 5.5 weeks of age caused a marked increase in NEFA levels after weaning but not in lambs weaned at 7.5 and 9.5 weeks of age. Lambs weaned at eight to nine weeks of age provided a high nutritive diet will have little to no fat mobilisation and are physiologically prepared for weaning (Earl *et al.*, 1990, Purchas, 1979). The shift in carcass fat will only be significant if it results in a lower fat grade at the point of slaughter which is dependent on the lambs opportunity to regain condition or minimise condition loss post-weaning (Geenty, 1980).

Table 4 The effect of different weaning ages on composition and conformation of lamb carcasses.

Trait/Study	Diet[1]	Weaning Age			Slaughter Age
		Early wean (5 to 8 weeks)	Conventional wean (9 to 11 weeks)	Not weaned	
Hind Limb Composition					
Muscle %					
Wong *et al.* (2018)	Herb mix	54.5	54.2	-	20 weeks
Cañeque *et al.* (2001)	P + S	66.9[a]	67.3[a]	63.7[b]	11 weeks
Bone %					
Wong *et al.* (2018)	Herb mix	7.1	6.8	-	20 weeks
Cañeque *et al.* (2001)	P + S	20.7	20.1	19.6	11 weeks
Fat %					
Wong *et al.* (2018)	Herb mix	9.2	9.8	-	20 weeks
Cañeque *et al.* (2001)	P + S	6.6[a]	8.3[b]	11.4[c]	11 weeks
Trimmed fat (g/kg)					
Wong *et al.* (2018)	Herb mix	92.6[b]	100.0[a]	-	20 weeks
Cañeque *et al.* (2001)	P + S	56.0[a]	71.5[b]	97.8[c]	11 weeks
Internal fat					
Omental fat (g/kg)					
Cañeque *et al.* (2001)	P + S	9.8[a]	12.0[b]	17.2[c]	11 weeks
Mesenteric fat					
Cañeque *et al.* (2001)	P + S	13.0[a]	13.7[a]	15.4[b]	11 weeks
Kidney knob and channel fat (g/kg)					
Cañeque *et al.* (2001)	P + S	11.2[a]	15.4[b]	24.3[c]	11 weeks
Sañudo *et al.* (1998b)	S	22.6[a]	-	32.2[b]	14 weeks
Munro and Geenty (1983)	P	9.7	-	-	18 weeks
Geenty (1979)	$P_{pre} + L_{post}$	9.2[a]	11.1[b]	13.7[b]	15 weeks
GR (mm)[2]					
Wong *et al.* (2018)	Herb mix	6.8[a]	8.2[b]	-	20 weeks
Cañeque *et al.* (2001)	P	1.1[a]	1.4[ab]	2.3[b]	11 weeks
Munro and Geenty (1983)	P	5.6	-	-	18 weeks
Geenty (1979)	$P_{pre} + L_{post}$	5.3[a]	9.6[b]	10.3[b]	15 weeks
Subjective fat score[3]					
Ekiz *et al.* (2012)	S	6.9[a]	7.0[a]	7.9[b]	17 weeks
Cañeque *et al.* (2001)	P + S	1.6[a]	1.9[b]	2.2[c]	11 weeks
Sañudo *et al.* (1998b)	S	3.1[a]	-	3.4[b]	14 weeks
Conformation score[4]					
Ekiz *et al.* (2012)	S	1.1[a]	1.2[ab]	1.2[b]	17 weeks
Sañudo *et al.* (1998b)	S	3.2[a]	-	3.4[b]	14 weeks

1. Diet: P = grass-based pasture, S = supplemented lucerne hay and concentrate, P_{pre} + L_{post} = grass-based pasture pre-weaning and lucerne post-weaning, Herb mix = plantain, chicory, white clover and red clover
2. GR: soft tissue depth over the 12th rib 11 cm from the midline
3. Subjective fat score classified using a scale: 1-15 (Ekiz *et al.*, 2012), 1-4 (Cañeque *et al.*, 2001), 1-5 (Sañudo *et al.*, 1998b)
4. Conformation score classified using a scale: 1-15 (Ekiz *et al.*, 2012), 1-5 (Sañudo *et al.*, 1998b)

$^{a, b, c}$ superscripts that are different indicate means are significantly different ($P < 0.05$) within each study

2.5 Effect of lamb growth on meat quality

Fast growing lambs produce heavier carcasses at slaughter yielding a higher total saleable meat yield compared to slow growing lambs (Campbell *et al.*, 2012). High growth rates and high meat yields can negatively influence meat quality in beef, pork and poultry (Dransfield and Sosnicki, 1999). Taste panels have recorded overall acceptability scores for lamb meat based on aroma, flavour, texture and succulence, and noted a lower overall acceptability score for fast growing lambs (2.30), growing at 280-350 g/day, compared to slow growing lambs (2.41), growing at 190-250 g/day (Campbell *et al.*, 2012). In comparison, objective measurements for meat quality traits such as meat redness, colour deterioration, brightness, and tenderness, did not differ between the two groups. Normal pH values for sheep meat range between 5.50 and 5.80 (Johnson *et al.*, 2017). Ultimate pH values from fast and slow growing lambs are within this range, where fast growing lambs have a lower pH level (5.77) compared to slow growing lambs (5.87) (Campbell *et al.*, 2012). Lamb growth performance has no negative effect on meat quality when measured objectively, however, subjective analysis show that it may be more beneficial to grow lambs between 190-250 g/day to ensure meat is acceptable (Campbell *et al.*, 2012).

Lamb growth rate and GR fat depth influence meat tenderness as shear force values increase by 0.44 kgF for every 50 g of live weight gained/day and decreases by 0.30 kgF for every millimetre increase in GR fat depth (Campbell *et al.*, 2011). Lambs grazing perennial ryegrass pasture losing 1 kg live weight during a 6-week finishing period produced slightly tougher meat, with a minor effect on meat eating quality, compared to lambs gaining 6 kg live weight. This could be attributed to the different carcass fat percentages between the two groups (Kirton *et al.*, 1981). Similarly, bodyweight loss followed by compensatory gain has no effect on meat tenderness (Winter, 1970). The extent to which lamb growth performance effects certain meat quality attributes such as tenderness will depend on the amount of intramuscular fat deposited (Hopkins *et al.*, 2006).

2.6 Effect of forage diets for lamb on meat quality

2.6.1 Ultimate pH

The rate at which muscle pH declines and the final value it reaches can influence storage life, consumer preference and meat eating quality (Bray *et al.*, 1994). For example, low ultimate pH values in pork produce pale, soft, and exudative meat where high ultimate pH values produce dark, firm, and dry meat (Bray *et al.*, 1994). It should be noted that the extent of these observations may not be observed in lamb meat with pH values outside the optimal range, but will have a negative influence on meat quality and the extent will depend on the final pH value (Bray *et al.*, 1994). Ultimate pH is the main driver for some meat quality characteristics such as colour, tenderness and water holding capacity (Schreurs *et al.*, 2013) and can be influenced by pre-slaughter factors such as under-nutrition and stress (Campbell *et al.*, 2011). Animals used in the studies were fed *ad lib* and slaughtered according to commercial standards for New Zealand lamb which in part can explain the optimum pH values observed (Table 5). Schreurs *et al.* (2013) recorded pH values slightly above the optimum level, for lambs which grazed plantain-clover (5.82) or perennial ryegrass-white clover pasture (5.83) but are unlikely to have a significant impact on meat quality attributes. Mean pH values, for plantain-clover and perennial ryegrass-white clover pasture are very similar and do not exceed 5.8 (Table 5). Suggesting that there is little to no difference in ultimate pH of lambs reared on either forage, with values under 5.8 showing both forages do not negatively influence pH values, producing meat which will suit consumer preference and not negatively influence meat eating quality.

Table 5 Ultimate pH of lambs finished on either perennial ryegrass pasture (perennial ryegrass and white clover; Rye/WC) or a plantain-clover mix (plantain, red and white clover; Plantain/C) during summer (December to February) and autumn (March to May).

Study	**Finishing period (days)**	**Age at slaughter (months)**	**pH**	
			Plantain/C	Rye/WC
Summer				
Mashele *et al.* (2017)	45	5	-	5.54
Kim *et al.* (2013)	84	6.5	5.71[b]	5.80[a]
Campbell *et al.* (2011)	42	6	5.59	5.62
Autumn				
Schreurs *et al.* (2013)	35	7	5.82	5.83
Average	**52**	**6.1**	**5.71**	**5.70**

[a, b] superscripts that are different indicate means within rows are significantly different ($P<0.05$) within each study

2.6.2 Meat colour

Meat colour is an important factor effecting consumer preference for red meat and purchasing decisions. Research presented (Table 6) show little to no variation in meat colour of lambs finished on either plantain-clover or perennial ryegrass-white clover pasture which indicate there is little difference between meat lightness, redness and yellowness of lambs finished on either of these finishing forages and plantain-clover having no noticeable negative effect on meat colour.

Meat redness (a*) increases with animal maturity due to an increase in myoglobin formation (Hopkins *et al.*, 2007). Lamb age at slaughter can therefore explain the different redness values observed between studies (Table 6). Younger animals tend to present lighter meat (i.e. higher L* values), where older animals may also present meat with lighter colour due to higher intramuscular fat which can attribute for the higher yellowness of fat in older lambs, therefore it can be expected that forage can have an effect through age at slaughter (Mashele *et al.*, 2017). Research presented (Table 6) support these statements showing both young and older lambs, age 5 and 7 months, to have lighter meat colour, 37.9 and 40.9 respectively. This suggests that when using a set weight slaughtering policy it can be expected that some lambs will be finished across several months from early summer to late summer into the autumn causing a age difference at slaughter. Lamb age could affect meat colour but given the young age of lambs at slaughter and the minor age difference it is unlikely to have a significant effect on meat colour.

Table 6 Meat colour of lambs grazing perennial ryegrass pasture (perennial ryegrass and white clover; Rye/WC) or a plantain-clover mix (plantain, white clover and red clover; Plantain/C) during summer (December to February) and autumn (March to May).

Study	**Finishing period (days)**	**Age at slaughter (months)**	**L***		**a***		**b***	
			Plantain/ C	Rye/WC	Plantain/ C	Rye/WC	Plantain/ C	Rye/WC
Summer								
Mashele *et al.* (2017)	45	5	-	37.8	-	13.2	-	3.6
Kim *et al.* (2013)	84	6.5	-	-	25.5	25.7	-	-
Campbell *et al.* (2011)	42	6	41.6	41.4	22.2	21.1	-	-
Autumn								
Schreurs *et al.* (2013)	35	7	41.6	40.9	15.3	14.8	-	-
Average	**52**	**6.1**	**41.6**	**40.0**	**21**	**18.7**	**-**	**3.6**

[a, b] superscripts that are different indicate means within rows are significantly different ($P<0.05$) within each study

Changes in a* and b* over time reflects the degree of meat colour deterioration from red to brown and assesses the myoglobin concentration and redox state in meat (Luciano *et al.*, 2009). Hue angle indicates meat browning, where larger angles signify browner meat due to a shift to yellow hue (Luciano *et al.*, 2009). A negative relationship occurs between hue angle and pigment concentration in red meat, where haem concentration decreases and metmyoglobin percentage increases over a 14-day period which can attribute for a decrease in meat redness, increase in yellowness and an increase in hue angle over time (Lindahl *et al.*, 2001, Luciano *et al.*, 2009).

Dietary tannins contain antioxidant properties which can influence meat colour stability (Kim *et al.*, 2013). Chemical analysis show plantain contains low levels of condensed tannins, ranging between 4 to 10 g/kg DM (Stewart, 1996). Deaker (1994) recorded a similar level of 9.55 g/kgDM. Furthermore, Farouk *et al.* (2007) found no effect of forage tannins on meat colour stability when comparing meat from lambs grazing lotus (containing 8.3 g/kgDM) and perennial ryegrass (containing no condensed tannins). Lambs supplemented with condensed tannins (quebracho, 100g/kgDM) produce lighter meat with decreased haem concentration and lower hue angles after seven and 11-days of storage, delaying the rate of meat browning (Luciano *et al.*, 2009). Indicating that a high concentration of condensed tannins is required to delay meat colour deterioration and forages may not contain sufficient levels of condensed tannins to effect meat colour stability.

2.6.3 Tenderness

Meat tenderness decreases as the animal ages due to increased cross-linking of collagen fibres as the animal gets older. Extensive cross-linking of collagen fibres decreases collagen solubility during cooking and increase the perception of meat toughness which reduces meat eating quality (Mashele *et al.*, 2017). Mashele *et al.* (2017) observed collagen solubility declined and IMF% increased with maturity.

Intramuscular fat can also influence meat tenderness (Schreurs *et al.*, 2013, Hopkins *et al.*, 1995). Intramuscular fat tends to increase with animal age (Mashele *et al.*, 2017), diluting muscle fibres which contain collagen and increases muscle toughness. High intramuscular fat content (>5%; (Hopkins *et al.*, 2006)) lowers the number of muscle fibres in a cross sectional area reducing the toughening effect of muscle fibres (Nishimura *et al.*, 1999). In addition, intramuscular fat has a lubricating effect, when melted it reduces the amount of force required to chew the meat increasing the perception of tenderness (Blumer, 1963, Hopkins *et al.*, 2006). Lambs used in the studies (Table 7) were slaughtered between five to seven months of age and it is possible that the variation in tenderness could be attributed to collagen solubility and IMF%. The forage diet can therefore influence tenderness indirectly by changing carcass composition through decreasing the muscle fibre concentration and increasing IMF levels.

Shear force values <5 kgF are considered as having better eating quality and associated with tender meat compared to meat with shear force values >5 kgF which tend to be perceived as tough in sensory tests (Hopkins *et al.*, 1995). Therefore, in Table 7, meat from lambs in Schreurs *et al.* (2013) could be considered more tender compared to meat from lambs in Mashele *et al.* (2017) and Campbell *et al.* (2011). Mean shear force values for plantain-clover and perennial ryegrass-white clover pasture (5.37 and 6.10 kgF respectively) are only slightly higher than 5 kgF therefore meat from lambs reared on either plantain-clover or pasture could still be considered tender. With average values showing lambs reared on plantain-clover are more likely to produce tender meat (5.37 kgF) compared to lambs finished on perennial ryegrass-white clover pasture (6.10 kgF, Table 7).

Table 7 Meat tenderness (measured by shear force, kgF) from lambs grazing perennial ryegrass pasture (perennial ryegrass and white clover; Rye/WC) or a plantain-clover mix (plantain, white clover and red clover; Plantain/C) during summer (December to February) and autumn (March to May).

Study	Finishing period (days)	Age at slaughter (months)	**Shear force (kgF)**	
			Plantain/WC	Rye/WC
Summer				
Mashele *et al.* (2017)	45	5	-	6.87
Campbell *et al.* (2011)	42	6	7.75	7.65
Autumn				
Schreurs *et al.* (2013)	35	7	2.98[b]	3.77[a]
Average	**41**	**6**	**5.37**	**6.10**

[a, b] superscripts that are different indicate means within rows are significantly different (P<0.05) within each study

2.6.4 Water holding capacity

Water holding capacity (WHC) of meat affects consumer preference (Clarke *et al.*, 1996). Objective meat quality measurements of lambs reared on plantain-clover or perennial ryegrass-white clover pasture showed no difference in expressible water of meat (Schreurs *et al.*, 2013). Likewise, Farouk *et al.* (2007) recorded similar values for expressible water and cooking loss for meat from lambs finished on *Lotus pedunculatus*, perennial ryegrass and white clover. A trained sensory panel found no difference in succulent scores of meat from lambs reared on plantain and perennial ryegrass pasture (Kim *et al.*, 2013). Studies have also investigated the effect of weaning age on WHC of lamb meat, where meat from lambs weaned at six and nine weeks of age or slaughtered directly at weaning did not differ in WHC (Cañeque *et al.*, 2001, Sañudo *et al.*, 1998b). These studies suggest that rearing lambs on either plantain-clover or perennial ryegrass-white clover pasture and weaning lambs at six or nine weeks of age will have little to no effect on the WHC of lamb meat.

2.6.5 Sarcomere length

Muscle sarcomere length is highly variable at slaughter until 24 hours post-mortem and the degree of shortening during rigor development determines the extent of meat toughening 0-24 hours post-mortem (Koohmaraie *et al.*, 2002). Lambs grazing perennial ryegrass-white clover pasture or plantain-clover produced meat with relatively similar sarcomere lengths, 1.72 and 1.75 µm respectively (Schreurs *et al.*, 2013). In addition, lambs weaned at nine weeks of age produced muscle fibres 0.12 µm longer compared to muscle fibres of lambs slaughtered directly at weaning, with an average muscle fibre length of 1.59 µm from both groups (Purchas, 1979). The difference in sarcomere length had no effect on shear force and therefore no negative effect on meat tenderness (Purchas, 1979). Furthermore, these values are within the recommended range, 1.69 µm and 2.24 µm, and could contribute to low shear force values (Koohmaraie *et al.*, 2002). It could be said that the forage grazed has a minimal effect on sarcomere length of lamb meat and the degree of muscle shortening will depend on slaughter conditions (Mashele *et al.*, 2017). Lambs used in the studies above were slaughtered according to commercial standards for New Zealand lamb which could further explain the little difference in sarcomere length (Schreurs *et al.*, 2013).

2.7 Influence of lamb weaning age on meat quality

Studies have shown weaning age does not have a significant effect on lamb meat quality. Lambs weaned at six weeks of age compared to lambs not weaned and slaughtered at 14 weeks of age produce similar ultimate pH, colour, WHC, and peak shear force values (Sañudo *et al.*, 1998b). Likewise, lambs weaned at six and nine weeks of age, compared to lambs still with their dam with all lambs slaughtered at 11 weeks of age produced meat with similar pH, redness, and WHC where meat from lambs not weaned was lighter with less collagen compared to lambs weaned at six and nine weeks of age (Cañeque *et al.*, 2001). Purchas (1979) also noted no difference in sarcomere length and peak shear force of meat from lambs weaned at nine weeks of age and lambs slaughtered at weaning, with both treatment groups slaughtered at 14 weeks of age. The literature shows weaning age and slaughtering at weaning has little effect on meat quality characteristics; however, few studies have considered the effect of weaning age and slaughtering lambs at a minimum set live weight and the influence on meat quality.

Chapter 3: Research Objectives

Previous research supports the use of alternative forages, such as herb-legume swards, to improve lamb performance and carcass characteristics in commercial sheep production systems. Few studies have aimed to determine how weaning practices and forage diet, together, impacts carcass and meat quality characteristics. Specifically, the influence of early weaning, at eight weeks of age with the use of forage diets with a higher feeding value than grass pastures, on the carcass composition and meat quality are not well known.

It is hypothesised that weaning lambs early (at eight weeks of age) onto a plantain-clover mix can produce lambs that have similar carcass and meat quality characteristics compared to lambs that are weaned conventionally (at approximately 14 weeks of age) onto perennial ryegrass-white clover pasture.

The objective of this research is:

1. To determine if weaning lambs at eight compared to 14 weeks of age has an influence on carcass and meat quality.
2. To compare differences in carcass and meat quality of lambs grown on a plantain-clover mix compared to perennial ryegrass-white clover pasture.

The key results in this thesis are the measures of carcass and meat quality however, some measures of growth performance are also indicated for completeness and to help explain the carcass and meat quality results. Results from the research will have the potential to validate farm weaning strategies and inform farmers of appropriate management of lambs to optimise farm production and profitability.

Chapter 4: Materials and Methods

4.1 Experimental design

The study was conducted at Massey University's Tuapaka farm, located approximately 15 km north-east of Palmerston North, New Zealand. Forty-three Romney ewes rearing twin lambs (86 lambs) were used in this study (MUAEC No 15/63). Ewes with lambs at foot grazed perennial ryegrass-white clover pasture prior to the study. At the start of the study (31 October) when lambs were approximately eight weeks of age and weighed more than 16 kg, the ewes, and their lambs, were allocated to one of four treatments:

1. Lambs weaned early (eight weeks of age; 31 October) onto a plantain-clover mix (EARLY) (lambs n=23)
2. Lambs with their dam grazing a plantain-clover mix (HERB) (lambs n=29)
3. Lambs with their dam grazing perennial ryegrass-white clover pasture >1200 kgDM/ha (HIGH) (lambs n=22)
4. Lambs with their dam grazing perennial ryegrass-white clover pasture <1200 kgDM/ha (LOW) (lambs n=12)

Lambs from the HERB, HIGH, and LOW treatments were not weaned until 14 weeks of age (12 December). There was an unexpected loss of one lamb in each of the HERB and EARLY treatments, hence, the uneven number of lambs for these treatments. Treatments were balanced for sex of the lamb. During the course of the study forage diets were offered *ad libitum* for animals in the EARLY, HERB, and HIGH treatments using rotational grazing. *Ad libitum* conditions of perennial ryegrass-white clover pasture was ensured by providing ewes and lambs with pasture >1200 kg DM/ha (Morris and Kenyon, 2004) and herb mixes with sward heights >7 cm (Somasiri *et al.*, 2016). The LOW treatment was selected to simulate poor spring pasture growth, where pasture covers on sheep farms can be restricted to 800-1000 kg DM/ha. The LOW treatment provides a comparison to show if early weaning is useful during poor late spring/early summer conditions and when pasture covers are restricted.

At the start of the experiment (31 October) two lambs in the HERB treatment were not found at weighing. At the second weighing (12 December) one lamb in the HERB treatment and one in the HIGH treatment was also not present. As a result, daily live weight gain could not be calculated for these animals and they were excluded from the calculations.

Post-treatment and slaughter management

At 14 weeks of age (12 December) all lambs were weighed and lambs weighing more than 35 kg were sent for slaughter (n=19; first slaughter). Growth rate (average daily gain; ADG) for the treatment period was calculated by subtracting the live weight at the start of the experiment (week 8) from the pre slaughter live weight at the first slaughter (week 14) and dividing by the number of days lambs spent on the treatments (42 days; Equation 1). Following the first slaughter at the end of the treatment period all remaining lambs were managed and finished together as one mob on high-quality perennial ryegrass-white clover pasture (>11 MJ ME) for six weeks to ensure lambs reach the minimum set slaughter weight of 35 kg. After six weeks (24 January) the remaining 67 lambs reached the target slaughter weight (>35 kg) and were sent for slaughter (second slaughter). The ADG for the duration of the finishing period (42 days) was calculated using Equation 2. In addition, ADG was also calculated for the entire study (84 days) using Equation 3.

Equation 1:

$$\mathrm{ADG}_{8\text{ to }14\text{ weeks}} = \frac{\text{pre slaughter live weight (week 14)} - \text{live weight at the start of the experiment (week 8)}}{\text{number of days}}$$

Equation 2:

$$\mathrm{ADG}_{14\text{ to }20\text{ weeks}} = \frac{\text{pre slaughter live weight (week 20)} - \text{live weight following 1st slaughter (week 14)}}{\text{number of days}}$$

Equation 3:

$$\mathrm{ADG}_{8\text{ to }20\text{ weeks}} = \frac{\text{pre slaughter live weight (week 20)} - \text{live weight at the start of the experiment (week 8)}}{\text{number of days}}$$

Lambs were slaughtered at a commercial abattoir (Alliance Group, Dannevirke) using electrical stunning followed by exsanguination. Carcasses were dressed according to commercial standards for New Zealand lamb. Carcasses were assigned an identification number which was linked to the electronic ID of each lamb allowing individual sheep to be tracked through the processing chain. Hot carcass weight was measured at the processing plant. The DO% was calculated as the proportion of the hot carcass weight in the live weight measured on-farm prior to slaughter and expressed as a percentage (Equation 4).

Equation 4:

$$\text{Dressing out (\%)} = \frac{\text{hot carcass weight}}{\text{on farm pre slaughter live weight}} \times 100$$

The GR soft tissue depth was estimated at the 12th rib 11 cm from the midline using the Alliance Group VIAscan system (Hopkins *et al.*, 2004). The VIAscan system was also used to estimate leg, shoulder, loin, and total meat yield of individual carcasses. Carcasses were chilled at 4°C for 24 hours and then the left hind leg (bone-in, short leg) was collected, vacuum packed with their respective carcass identification tag and frozen at -20°C.

Slaughter weight of one HERB lamb was not recorded at first slaughter and therefore DO% could not be calculated for this animal. Lastly, VIAscan data was not recorded for two lamb carcasses from the LOW treatment. Since all lambs were slaughtered at either 14 or 20 weeks of age, carcass and meat quality traits were measured for all hind leg samples.

4.2 Leg dissection to measure carcass characteristics

Hind leg samples were dissected over a 6-week period with the treatments balanced across the days of analysis. Hind leg samples were thawed at 1°C for 24 hours prior to dissection. The leg was dried with paper towels and weighed. The leg was dissected into eight muscles (gracillis, sartorius, pectineus, adductor, semimembranosus, semitendinosus, biceps femoris and quadriceps), additional muscles around the pelvic region (other) as well as the tibia and its associated muscles were also weighed and recorded. The trimmed fat was collected, weighed, and expressed as a percentage of the total leg (Equation 7). The femur bone length and weight was recorded to obtain the muscle to bone ratio (M:B) for each leg sample using Equation 5 (Johnson *et al.*, 2005). Muscularity of the hind leg was obtained by taking the muscle depth and dividing by bone length to obtain the amount of muscle per unit of bone length using Equation 6 (Purchas *et al.*, 1991). Lean meat yield percentage was calculated using M:B and trimmed fat% (Equation 8) and muscle percentage was calculated using the muscles associated with the femur (adductor, semimembranosus, semitendinosus, biceps femoris, and quadriceps femoris, gracilis, sartorius, and other) (Equation 9).

Equation *5:*

$$\text{M:B} = \text{muscle weight: bone weight}$$

Where: - Muscle weight = adductor + semimembranosus + semitendinosus + biceps fermoris + quadriceps fermoris

- Bone weight = femur weight

Equation 6:

$$\text{Muscularity} = \sqrt{\text{muscle weight} \times (\text{bone length}^{-1})} \times \text{bone length}^{-1}$$

Equation 7:

$$\text{Fat (\%)} = \frac{\text{trimmed fat weight}}{\text{leg weight}} \times 100$$

Equation 8:

$$\text{Lean meat yield (\%)} = (100 - \text{Trimmed fat\%}) \times (\frac{\text{M:B}}{\text{M:B+1}})$$

Equation 9:

$$\text{Muscle (\%)} = (\frac{\text{femur muscles}}{\text{pat dry leg weight} - \text{tibia and associated muscle}}) \times 100$$

Where: Femur muscles = gracilis + sartorius + pectineus + adductor + semimembranosus + semitendinosus + biceps femoris + quadriceps femoris + other

4.3 Meat quality tests

The *M. semimembranosus* that was dissected from each leg, vacuum packed and frozen for meat quality analysis at a later time. Objective meat quality measurements were done over a 3-week period with treatments balanced across the days of analysis. The vacuum-packed muscle was thawed at 1°C for 24 hours prior to analysis. Figure 1 illustrates sub-sampling of the *M. semimembranosus* muscle for objective meat quality tests which include ultimate pH, colour, sarcomere length, shear force, drip loss and intramuscular fat (IMF).

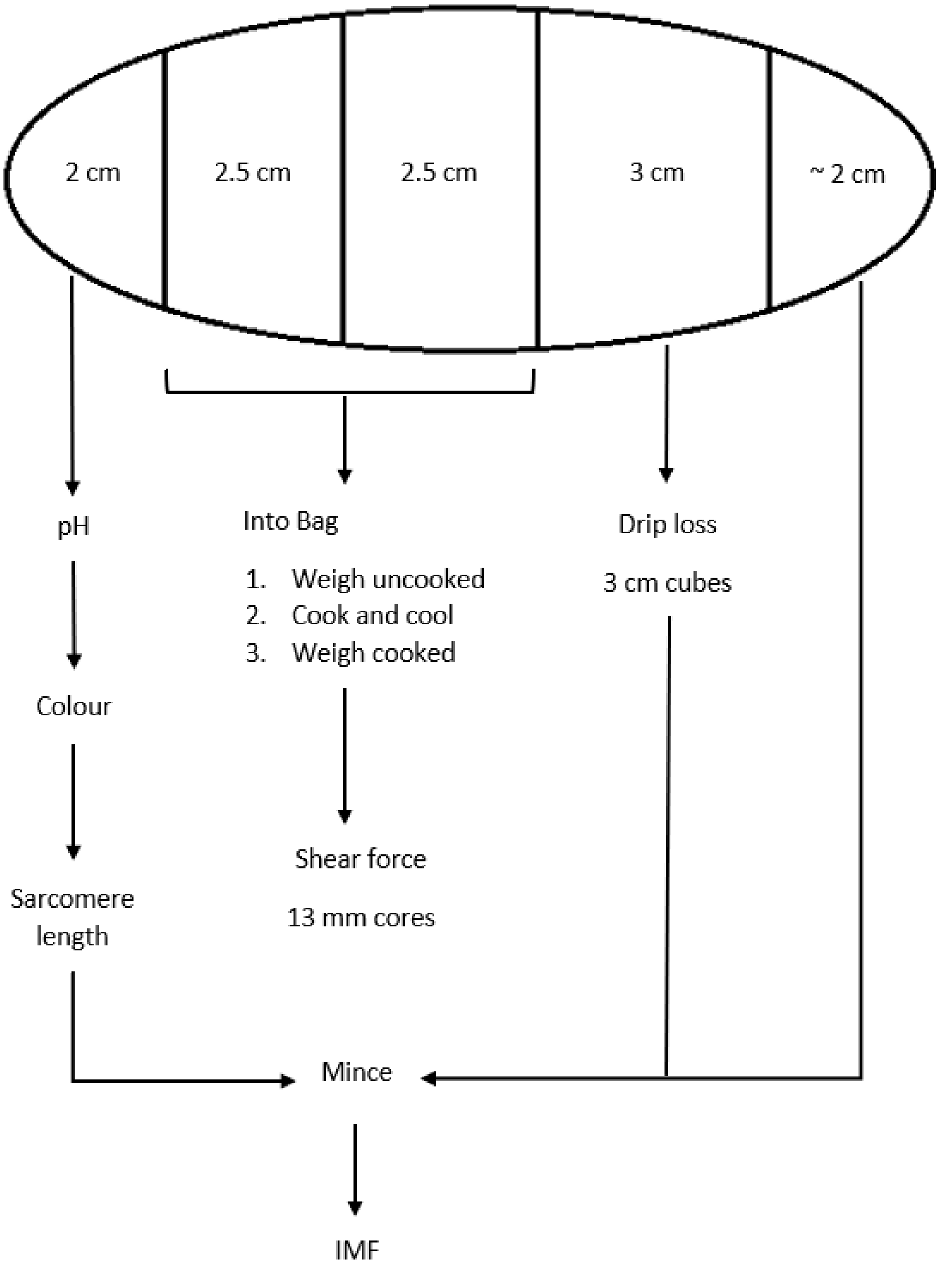

Figure 1 Sub-sampling of the *M.semimembranosus* muscle for meat quality analysis

Remaining meat from the *M. semimembranosus* muscle (after meat quality analysis) was minced (Kenwood MG450, 3mm hole-plate), vacuum packed and frozen for IMF analysis by ether extraction (AOAC 911.30). For IMF analysis; ten individual samples were randomly selected from five ram and five ewe lambs within each treatment.

4.3.1 Ultimate pH

Ultimate pH was measured on a 2 cm slice of the *M. semimembranosus* muscle using a pH spear (Eutech Instruments, Singapore) calibrated with standard buffers at pH 4, 7, and 10. Three measurements across a transverse cut were averaged to achieve the pH value for each sample.

4.3.2 Meat colour

The *M. semimembranosus* was cut and after 30 minutes exposure to air, the lightness (L*), redness (*a**), and yellowness (*b**) were measured using a Minolta CR-200 Chromometer (Konica Minolta. Mahwah, NJ, USA) calibrated to a white calibration plate supplied by the manufacturer. Three measurements were taken across the transverse cut and averaged to achieve a colour value for each muscle sample. Average redness (a*) and yellowness (b*) values were used to calculate the hue angle and chroma for each sample. Hue angle was calculated by the inverse tan of b* divided by a* and multiplied by a standard value, 57.296 (Equation 10). Chroma was calculated as the square root of the sum of the squared a* and b* values (Equation 11).

Equation 10:

$$\text{Hue angle } (^\circ) = (\tan^{-1}(\frac{b^*}{a^*})) \times 57.296$$

Equation 11:

$$\text{Chroma} = \sqrt{((a^*)^2 + (b^*)^2)}$$

4.3.3 Water holding capacity

Water holding capacity was determined by measuring thaw loss, drip loss, and cooking loss. Thaw loss from the hind leg was measured by difference from the packaged leg, pat dried leg and paper towel dried package weight, and expressed as a percentage (Equation 12). Likewise, thaw loss from the *M. semimembranosus* muscle was measured by difference from the packaged *M. semimembranosus*, pat dry *M. semimembranosus* and paper towel dried package weight and expressed as a percentage (Equation 13). Both thaw loss percentages were added together as an indicator of the potential total thaw loss from two freeze thaw steps (Equation 14).

Equation *12:*

$$\text{Thaw loss of hindleg } (\%) = \frac{\text{packaged leg} - (\text{pat dry leg} + \text{dried package})}{(\text{pat dry leg} + \text{dried package})} \times 100$$

Equation 13:

$$\text{Thaw loss of M. semimembranosus } (\%) = \frac{\text{packaged muscle} - (\text{pat dry muscle} + \text{dried package})}{(\text{pat dry muscle} + \text{dried package})} \times 100$$

Equation 14:

$$\text{Total thaw loss (\%)} = \text{leg thaw loss \%} + \text{semimembranosus thaw loss \%}$$

The drip loss was measured using meat cubes with 3 cm sides with visual fat and connective tissue trimmed. The meat cube was suspended from a metal hook in a plastic bag without the meat cube touching the plastic bag and chilled at 1°C. Initial weight and weight after 24 and 48 hours, was recorded and the water lost expressed as a percentage of the meat cube weight (Equation 15).

Equation 15:

$$\text{Drip loss (\%)} = \frac{\text{start weight} - \text{weight at 24 hours or 48 hours}}{\text{start weight}} \times 100$$

Cooking loss was also measured from cooked *M. semimembranosus* slices (two 2.5 cm slices) by difference of muscle weight before and after cooking and expressed as a percentage (Equation 16).

Equation 16:

$$\text{Cooking loss (\%)} = \frac{\text{weight before cooking} - \text{weight after cooking}}{\text{weight before cooking}} \times 100$$

4.3.4 Tenderness

M. semimembranosus slices, 2.5 cm thick, were placed in a plastic bag and cooked in a water bath at 70°C for 90 minutes (Contherm®, Model 370HL, Australia). A corer was used to prepare 13 mm diameter cylindrical cores parallel to the muscle fibre direction. Peak shear force and total shear force work (TMS-Pilot Texture analyser, USA) were recorded. Peak shear force measures the amount of force required to shear through the sample core, compared to total shear force work which measures the total amount of force applied over time on the sample core. Six cores per muscle sample were used to measure the force required to shear through the cores perpendicular to the muscle fibre direction. The six replicate measurements (one shear per core) were averaged.

4.3.5 Sarcomere length

A muscle bundle was dissected from the *M. semimembranosus* and prepared by teasing out the muscle fibres with scalpel blades on a glass slide. Two drops of water were added, and the sample compressed between two microscope slides. A helium-neon laser (632.8 nm, Melles Griot, Carlsbad, CA, USA) was passed through the sample and the sarcomere length determined by measuring the distance between the first-order diffraction bands in millimetres (mm). Ten replicates per sample were measured, averaged and the average value used to calculate the sarcomere length using Equation 17 (Bouton *et al.*, 1973).

Equation *17:*

$$\text{Sarcomere length } (\mu\text{m}) = 0.6328 \times \frac{\sqrt{\left(\left(\frac{x}{10\times2}\right)^2 + 100\right)}}{\frac{x}{10\times2}}$$

Where: x = Average of the ten replicate measurements

4.4 Statistical analysis

Carcass and meat quality characteristics were analysed using general linear models (PROC GLM, SAS) in SAS 9.4 with treatment as the fixed effect (see Appendix 1). Slaughter age was initially fitted as a covariate to carcass and meat quality characteristics and found to be non-significant (P>0.05) and so removed from the statistical model. Hot carcass weight was fitted as a covariate to carcass composition characteristics and pH was fitted as a covariate to meat-quality characteristics. If covariates were found to be non-significant (P>0.05) the covariate was removed from the statistical model and rerun.

Chapter 5: Results

5.1 Growth performance

As implemented in the experimental design, lamb live weight at the start of the treatment period was the same among treatments (P>0.05). During the eight-week treatment period (from 31 October to 12 December), HERB lambs grew faster than HIGH lambs (P<0.05), EARLY lambs had intermediate growth rates and LOW lambs had the slowest growth (P<0.05; Table 8). At the end of the treatment period (12 December) all lambs were weighed and lambs >35 kg were sent for slaughter (n=19; first slaughter). The proportion of lambs within each treatment that reached minimum set slaughter weight include, five lambs from the EARLY treatment (22% of lambs in treatment), 11 from the HERB treatment (38% of lambs in treatment), three from the HIGH treatment (14% of lambs in treatment), and no lambs from the LOW treatment.

During the six-week finishing period all lambs were grazed as one mob on perennial ryegrass-white clover pasture (from 13 December to 24 January), LOW lambs grew faster than EARLY and HERB lambs (P<0.05), and HIGH lambs had the slowest growth (P<0.05; Table 8). All remaining lambs reached the minimum set slaughter weight at the end of the study (24 January) (n=67; second slaughter). Over the entire experimental period, from eight to 20 weeks of age, HERB lambs grew faster than EARLY and HIGH lambs (P<0.05), and LOW lambs had the slowest growth (P<0.05). EARLY and HIGH lambs had similar growth rates when considering both the treatment and finishing periods (P>0.05; Table 8). Following the finishing period all remaining lambs were sent for slaughter and there was no difference in slaughter weight of lambs among treatments (P>0.05).

5.2 Carcass characteristics at slaughter

Hot carcass weight of HERB lambs was similar (P>0.05) to HIGH lambs and heavier (P<0.05) than EARLY and LOW lambs (Table 8). Likewise, DO% of HERB lambs were similar (P>0.05) to HIGH lambs and greater (P<0.05) than EARLY and LOW lambs (Table 8). VIAscan GR and leg, shoulder, loin, and total yield did not differ among treatments (P>0.05).

5.3 Carcass characteristics from leg dissection

Carcass weight was a significant covariate for most carcass characteristics measured during the dissections of the legs (P<0.05), except for sartorius weight and IMF% (Table 9), hence, carcass weight is a driver of the variation in carcass characteristics. The carcass weight covariate remained in the statistical model for the carcass characteristics determined by hind leg dissection to enable comparison at the same carcass weight. Hind leg weights were similar among treatments when compared at the same carcass weight (P>0.05). Likewise, the treatments had no effect on the weight of individual muscles of the hind limb and bone measurements, such as length, weight, and percentage when lambs are compared at the same carcass weight (P> 0.05). The weight of trimmed fat from the hind limb was similar (P<0.05) among HIGH and LOW lambs but heavier than that of EARLY lambs (P<0.05; Table 9). When expressed as a percentage of the leg weight, the trimmed fat% was greater in HIGH lambs (P<0.05) compared to EARLY and HERB lambs (P>0.05). The IMF% was similar among different treatments (P>0.05). Carcass indices of muscularity, muscle to bone ratio, and LMY%, did not differ among treatments (P>0.05), however, EARLY lambs had a 1.3% higher muscle% compared to HIGH lambs (P<0.05; Table 9).

5.4 Meat quality characteristics

Ultimate pH was similar between treatments (P>0.05) ranging between 5.46 to 5.53. Ultimate pH was a significant covariate for most meat-quality measures, except for cooking loss (P<0.05; Table 10). Peak shear force values were similar among treatments with an average peak force of 3.37 kgF (Table 10). Objective meat quality measures were similar among the treatments (P<0.05), except for sarcomere length and total shear force work (Table 10). Sarcomere length did not differ (P>0.05) between EARLY and HIGH lambs but was greater compared to HERB lambs (P<0.05). Total shear force work was greater (P<0.05) for HIGH lambs compared to EARLY, HERB and LOW lambs.

Table 8 Growth performance and carcass characteristics at slaughter (mean ± SEM) of lambs weaned early, at 8 weeks of age, onto a plantain-clover mix (EARLY), and conventionally weaned lambs, at 14 weeks of age, grazing a plantain-clover mix (HERB), grazing pasture >1200 kgDM/ha (HIGH) and pasture <1200 kgDM/ha (LOW). All lambs were slaughtered at a minimum set live weight >35 kg at 14 or 20 weeks of age.

		Treatment				**P value**	
Variable (unit)	n	EARLY (n=23)	HERB (n=29)	HIGH (n=22)	LOW (n=12)	Treatment	Hot carcass weight covariate[1]
Growth performance							
ADG $_{\text{8 to 14 weeks}}$ (g/day)	82	260.8 ± 7.6[c]	325.5 ± 7.2[a]	283.2 ± 8.0[b]	164.3 ± 10.6[d]	**<0.001**	-
ADG $_{\text{14 to 20 weeks}}$ (g/day)	67	183.6 ± 9.2[b]	165.3 ± 9.5[bc]	148.8 ± 9.5[c]	216.3 ± 11.6[a]	**<0.001**	-
ADG $_{\text{8 to 20 weeks}}$ (g/day)	86	219.5 ± 5.8[b]	241.4 ± 6.1[a]	217.3 ± 5.8[b]	190.3 ± 7.2[c]	**<0.001**	-
Number at slaughter 1	19	5	11	3	0		
Number at slaughter 2	67	18	18	19	12		
Slaughter weight (kg)[2]	85	38.2 ± 0.5	39.0 ± 0.5	38.3 ± 0.5	37.7 ± 0.7	0.397	-
Carcass characteristics							
Hot carcass weight (kg)	86	16.0 ± 0.3[b]	16.9 ± 0.2[a]	16.4 ± 0.3[ab]	15.7 ± 0.4[b]	**0.016**	-
Dressing out percentage (%)	85	41.9 ± 0.4[b]	43.5 ± 0.4[a]	42.9 ± 0.4[ab]	41.6 ± 0.6[b]	**0.011**	-
VIAscan yield							
GR (mm)	84	6.2 ± 0.6	6.0 ± 0.5	5.9 ± 0.6	6.0 ± 0.8	0.989	**<0.01**
Leg yield (%)	84	22.4 ± 0.3	22.4 ± 0.3	22.7 ± 0.3	22.7 ± 0.4	0.801	-
Loin yield (%)	84	14.8 ± 0.2	15.1 ± 0.2	14.9 ± 0.2	14.7 ± 0.2	0.560	-
Shoulder yield (%)	84	17.9 ± 0.2	18.1 ± 0.2	18.0 ± 0.2	17.9 ± 0.3	0.896	-
Total yield (%)	84	55.1 ± 0.6	55.5 ± 0.5	55.6 ± 0.6	55.3 ± 0.8	0.923	-

1. Covariate not fitted to the linear model when indicated by a dash
2. Slaughter weight: Lamb live weight prior to trucking for slaughter (at 14 or 20 weeks of age) once lambs reach a minimum set live weight > 35 kg

ADG (average daily gain): Week 8 (31 October), Week 14 (12 December), Week 20 (24 January)

[a, b, c, d] superscripts that are different indicate means within rows are significantly different between treatments (P<0.05)

Table 9 Carcass characteristics obtained from physical dissection of the hind limb (mean ± SEM) of lambs weaned early, at 8 weeks of age, onto a plantain-clover mix (EARLY), and conventionally weaned lambs, at 14 weeks of age, grazing a plantain-clover mix (HERB), grazing pasture >1200 kgDM/ha (HIGH) and pasture <1200 kgDM/ha (LOW). All lambs were slaughtered at a minimum set live weight >35 kg at 14 or 20 weeks of age.

Variable (unit)	n	Treatment				P value	
		EARLY (n=23)	HERB (n=29)	HIGH (n=22)	LOW (n=12)	Treatment	Hot carcass weight covariate[1]
Total leg (g)	86	2313 ± 20.1	2297 ± 18.3	2296 ± 20.4	2313 ± 28.1	0.909	**<0.001**
Muscles[2]							
Gracilis (g)	86	48.7 ± 0.8	47.9 ± 0.7	46.3 ± 0.8	47.0 ± 1.2	0.202	**<0.001**
Sartorius (g)	86	13.8 ± 0.5	13.3 ± 0.4	13.1 ± 0.5	12.4 ± 0.7	0.355	NS
Pectineus (g)	86	43.6 ± 1.1	41.0 ± 1.0	40.2 ± 1.1	40.6 ± 1.6	0.143	**<0.001**
Semimembranosus (g)	86	247.1 ± 3.7	245.0 ± 3.3	241.4 ± 3.7	246.4 ± 5.1	0.729	**<0.001**
Adductor (g)	86	114.3 ± 1.9	110.8 ± 1.7	107.4 ± 2.0	115.1 ± 2.7	0.051	**<0.001**
Biceps Femoris (g)	86	249.8 ± 3.6	242.3 ± 3.3	244.4 ± 3.6	247.7 ± 5.0	0.471	**<0.001**
Semitendinosus (g)	86	94.3 ± 1.7	92.6 ± 1.5	93.1 ± 1.7	96.9 ± 2.4	0.487	**<0.001**
Quadriceps (g)	86	373.1 ± 4.6	365.6 ± 4.1	368.9 ± 4.6	377.6 ± 6.4	0.423	**<0.001**
Other muscles (g)	86	344.9 ± 6.3	356.0 ± 5.7	342.6 ± 6.3	354.3 ± 8.7	0.345	**<0.001**
Femur bone							
Bone weight (g)	86	155.7 ± 2.3	155.0 ± 2.1	150.4 ± 2.3	150.2 ± 3.2	0.242	**<0.001**
Bone length (mm)	86	169.7 ± 1.0	169.0 ± 0.9	170.2 ± 1.0	169.7 ± 1.4	0.842	**<0.001**
Bone percentage (%)[3]	86	8.2 ± 0.1	8.2 ± 0.1	8.0 ± 0.1	8.0 ± 0.2	0.339	**<0.01**
Fat							
Trimmed fat weight (g)	86	201.9 ± 6.8^{b}	213.4 ± 6.4^{ab}	229.7 ± 6.7^{a}	231.2 ± 10.9^{a}	**0.007**	**<0.01**
Trimmed fat percent (%)	86	10.7 ± 0.4^{b}	11.3 ± 0.3^{b}	12.1 ± 0.4^{a}	12.0 ± 0.6^{ab}	**0.020**	**<0.05**
Intramuscular fat (%)	40	1.6 ± 0.2	1.7 ± 0.2	2.1 ± 0.2	2.0 ± 0.2	0.211	NS
Carcass indices							
Muscularity	86	0.47 ± 0.04	0.47 ± 0.04	0.46 ± 0.04	0.47 ± 0.06	0.585	**<0.05**
Muscle to Bone ratio	86	6.9 ± 0.1	6.8 ± 0.1	7.0 ± 0.1	7.2 ± 0.2	0.156	**<0.05**
Lean meat yield[4] (%)	86	77.9 ± 0.3	77.4 ± 0.3	76.9 ± 0.4	78.0 ± 0.5	0.136	**<0.01**
Muscle percent[5] (%)	86	80.9 ± 0.4^{a}	79.9 ± 0.3^{ab}	79.6 ± 0.4^{b}	80.3 ± 0.6^{ab}	**0.004**	**<0.01**

1. NS: Covariate is non-significant
2. Muscles surrounding the femur bone
3. Bone as a percentage of the hind limb $\left(\frac{Femure\ weight}{dry\ leg\ weight - tibia\ and\ associated\ muscles}\right) \times 100$
4. Calculated LMY using the equation $(100 - \text{Trimmed fat\%}) \times \left(\frac{\text{M:B}}{\text{M:B+1}}\right)$
5. Muscle% of muscles surrounding femur as a percentage of the hind leg less tibia and associated muscles calculated by $\left(\frac{\text{femur muscles}}{\text{dry leg weight} - \text{tibia and associated muscles}}\right) \times 100$

[a, b, c, d] superscripts that are different indicate means within rows are significantly different between treatments (P<0.05)

Table 10 Meat quality characteristics of the *M. semimembranosus* (mean ± SEM) of lambs weaned early, at 8 weeks of age, onto a plantain-clover mix (EARLY), and conventionally weaned lambs, at 14 weeks of age, grazing a plantain-clover mix (HERB), grazing pasture >1200 kgDM/ha (HIGH) and pasture <1200 kgDM/ha (LOW). All lambs were slaughtered at a minimum set live weight >35 kg at 14 or 20 weeks of age.

		Treatment				P value	
Variable (unit)	n	EARLY (n=23)	HERB (n=29)	HIGH (n=22)	LOW (n=12)	Treatment	Ultimate pH covariate[1]
pH	86	5.50 ± 0.03	5.48 ± 0.02	5.53 ± 0.03	5.46 ± 0.04	0.384	-
Meat colour							
*L**	86	39.9 ± 0.4	39.7 ± 0.3	39.9 ± 0.4	39.7 ± 0.5	0.991	**<0.001**
*a**	86	12.1 ± 0.2	12.5 ± 0.1	12.2 ± 0.2	11.9 ± 0.2	0.117	**<0.01**
*b**	86	3.0 ± 0.1	3.1 ± 0.08	2.9 ± 0.1	2.9 ± 0.1	0.151	**<0.001**
Hue angle	86	14.1 ± 0.4	14.1 ± 0.4	13.3 ± 0.4	13.5 ± 0.6	0.379	**<0.01**
Chroma	86	12.5 ± 0.2	12.9 ± 0.1	12.5 ± 0.2	12.2 ± 0.2	0.089	**<0.01**
Water-holding capacity							
Drip $loss_{24hr}$ (%)	86	3.8 ± 0.3	4.0 ± 0.3	3.7 ± 0.3	3.3 ± 0.4	0.561	**<0.01**
Drip $loss_{48hr}$ (%)	86	4.8 ± 0.4	5.2 ± 0.3	4.9 ± 0.4	4.4 ± 0.5	0.611	**<0.01**
Cooking loss (%)	86	37.7 ± 0.8	36.2 ± 0.7	37.5 ± 0.8	38.5 ± 1.1	0.256	NS
Thaw loss (%)[2]	86	0.89 ± 0.1	0.82 ± 0.09	0.83 ± 0.1	0.88 ± 0.1	0.952	**<0.001**
Thaw loss (%)[3]	86	6.3 ± 0.5	6.2 ± 0.4	6.4 ± 0.5	6.3 ± 0.6	0.989	**<0.001**
Total thaw loss (%)[4]	86	7.1 ± 0.5	7.0 ± 0.4	7.3 ± 0.5	7.2 ± 0.6	0.985	**<0.001**
Sarcomere length (μm)	86	1.74 ± 0.02[a]	1.68 ± 0.02[b]	1.75 ± 0.02[a]	1.73 ± 0.03[ab]	**0.025**	**<0.001**
Tenderness							
Total work	86	20.0 ± 1.6[b]	20.2 ± 1.4[b]	24.0 ± 1.7[a]	19.1 ± 2.3[b]	**<0.01**	**<0.01**
Peak force	86	3.2 ± 0.2	3.5 ± 0.2	3.4 ± 0.2	3.4 ± 0.3	0.808	**<0.001**

1. Covariate not fitted to the linear model when indicated by a dash, NS: Covariate is non-significant
2. Thaw loss % of the leg, at first thawing
3. Thaw loss % of the *M. semimembranosus*, at second thawing
4. The sum of leg thaw loss %, at first thawing, and *M. semimembranosus* thaw loss %, at second thawing

[a, b, c, d] superscripts that are different indicate means within rows are significantly different between treatments (P<0.05)

Chapter 6: Discussion

The study objective was to investigate if weaning age effects lamb carcass and meat quality characteristics and determine if there is a difference in carcass and meat quality of lambs grown on a plantain-clover mix compared to perennial ryegrass-white clover pasture. This was done by weaning lambs early, at eight weeks of age, onto a plantain-clover mix in comparison to weaning lambs at 14 weeks of age grazing a plantain-clover mix or perennial ryegrass-white clover pasture.

6.1 Lamb growth performance

During the eight-week treatment period, EARLY lambs grew faster than LOW lambs and slower than HIGH lambs, with HERB lambs growing faster compared to lambs from the other three treatments. The faster growth of lambs grazing the HERB treatment compared to lambs in the other treatments is likely attributed to two interacting factors, namely the higher feeding value of a plantain-clover mix (Kemp *et al.*, 2010) and the greater quantity of milk available to these lambs (Hutton *et al.*, 2011). A plantain-clover mix has a higher ME (MJ ME/kg DM) content; and better digestibility allowing for a greater voluntary intake (Speijers *et al.*, 2004) which contribute to greater milk production of the ewe and can promote growth when directly consumed by the lamb.

Cranston *et al.* (2016) noted that lambs suckling their dam grazing a plantain-clover mix or perennial ryegrass-white clover pasture grew faster compared to early weaned lambs grazing plantain-clover. Ewe milk provides more crude protein (246g/kg; (Danso *et al.*, 2018)) compared to a herb-legume mix (130 g/kg DM) or perennial ryegrass-white clover pasture (115 g/kg DM; (Hutton *et al.*, 2011)); hence, the supply of protein relative to metabolisable energy is higher in ewe milk compared to herbage which is efficiently utilised by the lamb for growth (Danso *et al.*, 2018). Early weaned lambs (at eight weeks of age) have no access to milk after weaning and rely on forage (in current study plantain-clover) for daily growth after eight weeks of age when the lambs' requirement for crude protein relative to metabolisable energy is like to still be above that which can be supplied from plantain-clover and perennial ryegrass-white clover pasture alone. Lambs weaned at 14 weeks of age have access to milk for a further six weeks which can, in part, this explains the faster growth of conventionally weaned lambs in the HERB and HIGH treatment compared to EARLY weaned lambs. Ewes grazing a herb-legume mix during lactation produce 17-25% more milk compared to ewes grazing perennial ryegrass pasture (Hutton *et al.*, 2011). The faster growth of lambs in the HERB treatment compared to lambs in the HIGH treatment is likely due to more milk produced and a higher intake of crude protein relative to metabolisable energy which increases lamb growth (Hutton *et al.*, 2011). In addition, lambs rely mainly on herbage for growth after eight weeks of age and lambs in the HERB treatment grazed a forage with a higher feeding value compared to lambs in the HIGH treatment which could also explain the superior growth of lambs in the HERB treatment.

Lambs in the LOW treatment, which were offered restricted feed intakes during the treatment period, grew faster during the finishing period compared to continuously fed lambs in the EARLY and HERB treatments, and HIGH lambs had the slowest growth. Given the feeding regime, the greater growth rate of LOW lambs could possibly be attributed to compensatory gain (Oldham *et al.*, 1999). Lambs restricted during pre-weaning maintain the potential to grow because of an increased efficiency of feed utilisation above the maintenance requirement during a period of unrestricted feeding and the rate of live weight gain after restriction will depend on the quality and quantity of forage provided (Meyer and Clawson, 1964).

6.2 Carcass characteristics

6.2.1 Carcass weight

Lambs in the EARLY and LOW treatments produced the lightest carcass weights compared to lambs in the HERB treatment which produced the heaviest carcass weights. The forage diet affects lamb growth which determines carcass weight at slaughter, hence, the forage diet can have an direct effect on carcass weight through lamb growth (Schreurs *et al.*, 2013). Lamb carcasses in New Zealand are graded based on carcass weight and subcutaneous fat cover (GR which is measured as the soft tissue depth at the 12th rib 11 cm from the midline). It should be noted that even though carcass weights were different, carcass weights between treatments differed by less than 1.3 kg which is unlikely to transverse carcass weight classes. Carcasses in the study are within the medium weight range (13.3-17.1 kg), with HERB lambs (16.9 kg) and HIGH lambs (16.4 kg) close to shifting into a heavier carcass weight class.

It should be noted that all lambs in the LOW treatment reached the minimum set slaughter weight >35 kg at the second slaughter date. This suggests that if a dam and her lambs are allocated to pasture covers <1200 kgDM/ha during the pre-weaning period and lambs are given the opportunity to be fed at an increased allowance or on a forage with a greater feeding value after weaning then the lambs can reach a minimum set slaughter weight >35 kg with little impact on carcass weight within six-weeks. Lambs in the EARLY and LOW treatments had a lower DO% compared to lambs in the HERB treatment. This is expected since a heavier carcass is associated with a higher DO% (Somasiri *et al.*, 2015a). Somasiri *et al.* (2015a) previously observed lambs finished on plantain-clover mixes produced heavier carcasses with higher DO% values compared to lambs finished on perennial ryegrass-white clover pasture. Soft tissue depth did not differ among treatments when adjusted for carcass weight which is likely a consequence of lambs being slaughtered at a set live weight >35 kg. A heavier carcass is associated with greater subcutaneous fat cover (Butler-Hogg and Johnsson, 1986) so the significant covariate effect of carcass weight on the soft tissue depth is logical.

6.2.2 Carcass composition

The study has shown that the type of forage provided has minimal effect on lamb carcass characteristics (see chapter 5, Table 8 and 9). Early weaned lambs produced less trimmed fat compared to HIGH and LOW lambs and as a result HERB and EARLY lambs had a lower trimmed fat% compared to HIGH lambs. Correspondingly, lambs in the EARLY treatment have a higher muscle% compared to HIGH lambs when compared at the same carcass weight. The significance of carcass weight as a covariate suggests that carcass composition can be attributed to carcass weight and potentially extent of growth prior to slaughter (Andrews and Ørskov, 1970).

Comparing lambs at the same carcass weight gave no difference in bone length, weight, and percentage among the treatments. The carcass weight was a significant covariate for bone weight and length and it is known that a heavier animal is likely to have a larger stature with longer bones which increases bone weight and bone percentage in the hind limb (Purchas *et al.*, 1991). Wong *et al.* (2018) noted lambs weaned at eight weeks of age onto a herb-mix produce heavier bones compared to lambs weaned at 14 weeks of age which grazed a herb-mix or perennial ryegrass-white clover pasture. The greater feeding value of a herb-mix compared to perennial ryegrass was noted as potentially affecting nutritional and hormonal factors that can influence bone ossification (Lewis *et al.*, 2004). A similar effect was not observed in the current study and it is not clear what is driving the different results and factors other than weaning age and diet and would need investigation.

Lambs in the EARLY treatment deposited less fat compared to HERB, HIGH and LOW lambs. Trimmed fat weight in the hind limb was numerically higher for lambs in the LOW and HIGH treatments compared to HERB lambs and can be attributed to the slower growth of LOW and HIGH lambs over the course of the study. Slow growing lambs are fatter at any given carcass weight (Kirton *et al.*, 1995) compared to fast growing lambs due to more fat in the gain (Campbell *et al.*, 2012, Searle *et al.*, 1982). The high fat weight in the leg of LOW lambs compared to HERB and EARLY lambs can therefore be attributed to their slower growth (Meyer and Clawson, 1964). In addition, the ability of LOW lambs to increase their feed intake during the finishing period in excess of their daily energy requirement is likely to contribute to the greater fat levels of these lambs compared to lambs in the other treatments (Greenwood *et al.*, 1998). This effect was not seen in EARLY lambs, which had similar growth rates to HIGH lambs (for the duration of the study) but produced less trimmed fat and trimmed fat% values. Milk promotes fat deposition because it is utilised more efficiently by the lamb and provides higher energy intakes compared to grass-based pasture (Sañudo et al., 1998), so it is likely that EARLY lambs were less fat due to less milk in their lifetime diet. Subcutaneous fat cover did not differ among treatments, therefore, the difference in trimmed fat weight and subsequently trimmed fat% can be attributed to intermuscular fat. Carcasses are graded based on weight and fat cover, therefore, the difference in trimmed fat weight and fat% is unlikely to cause a shift in carcass classification. Carcasses in the study can be classed as lean (6 mm fat cover) and require, on average, an additional 1.1 mm GR to shift to the prime grade (7.1-12 mm). The IMF depot is a late developing fat depot compared to the subcutaneous and intermuscular fat depots (Butler-Hogg and Johnsson, 1986) and with animals in the study slaughtered at five months of age, the low IMF levels (<5%; Hopkins *et al.* (2006)) are expected.

The muscularity of the hind limb did not vary between treatments, likewise, lambs with similar carcass weights grazing perennial ryegrass pasture or high nutritive forages, such as lucerne or red clover, had no difference in the *Longissimus dorsi* muscle depth in the study of Fraser *et al.* (2004). This suggests that the forage diet does not influence muscularity when comparing carcasses at the same weight. The significance of the carcass weight as a covariate shows that carcass indices are likely driven by carcass weight, where a heavier carcass is likely to have larger muscles with greater depth, higher M:B, lean meat yield and muscle% (Jones *et al.*, 2002). The results show muscle% of the hind limb varies among weaning age treatments, where EARLY lambs had the highest muscle%, with HERB and LOW lambs having intermediate values, and lambs in the HIGH treatment with the lowest muscle%. Muscularity did not differ between lambs among different treatments; therefore, it is likely that the difference in muscle% is attributed to a change in the fat% of the hind leg where an increase in carcass fat% will cause a decrease in carcass muscle% and vice versa (Purchas *et al.*, 1991). It was noted that the difference in muscle% did not cause a change in the VIAscan lean meat yield, suggesting that using a plantain-clover mix to increase lean meat yield of a carcass may not be more advantageous than perennial ryegrass-white clover pasture when lambs are slaughtered at a minimum set weight >35 kg. Although the higher nutritive value of a plantain-clover mix is likely to allow lambs to achieve a target slaughter weight sooner.

6.3 Meat quality characteristics

Ultimate pH values for lamb did not differ among forage and weaning age treatments. Some forage diets can influence the ultimate pH, but has not been observed to be different between lambs grazing plantain or perennial ryegrass pasture (Campbell *et al.*, 2011). Furthermore, the similar pH values observed are not surprising given the similar pre-slaughter conditions and treatment at slaughter (Campbell *et al.*, 2011).

The ultimate pH can affect important meat-quality traits such as colour, water-holding capacity, and tenderness (Schreurs *et al.*, 2013). The IMF% is another determinant of meat tenderness (Hopkins *et al.*, 2006). The treatments resulted in pH and IMF concentrations of the *M.semimembranosus* that were the same and so the similar shear force values reflect this. Shear force values are similar to those recorded by Purchas (1979) for the *M. semimembranosus* muscle of lamb and by Schreurs *et al.* (2013) for loin samples from lambs grazing perennial ryegrass-white clover pasture and plantain-clover mixes. Intramuscular fat deposition increases as the animals' degree of maturity increases and since the lambs were slaughtered at five months of age a similar degree of maturity was likely to prevent a greater IMF concentration. Even with low IMF levels (<5%; Hopkins *et al.* (2006)), shear force values were <3.4 kgF which is below the 5 kgF threshold considered as being required to have tender meat (Hopkins *et al.*, 1995). Similar to these findings, Hopkins *et al.* (1995) recorded low peak shear force values for six-month old lambs grazing chicory and lucerne (4.4 kgF and 4.2 kgF) and found no effect of the forage diet on meat tenderness. The low shear force values can therefore be attributed to the young age of lambs at slaughter (Hopkins *et al.*, 2006).

The forage treatments had an effect on sarcomere length and total shear force work. The sarcomere length even though statistically different, varied by less than 0.06 µm between treatments. This small difference is unlikely to affect meat quality characteristics and is likely to reflect normal variation in sarcomere length (Koohmaraie *et al.*, 2002). Total shear force work indicates the total amount of force applied during the shear force testing of the sample core and provides an indication of the amount of effort required to break down a piece of meat whilst chewing. Meat from lambs in the HIGH treatment required the greatest amount of total shear force work compared to meat samples from EARLY, HERB and HIGH lambs. This result is difficult to explain without further testing but suggests that other factors such as collagen or muscle fibre characteristics need to be considered as contributing to the shear force total work results for lambs on different forage or weaning age treatments (Mashele *et al.*, 2017).

6.4 Limitations in current study and future research

The trial design required lambs to reach a minimum set slaughter weight at two different slaughter dates 42 days apart, this can be considered a limitation since using two slaughter dates could have allowed lambs that weighed slightly less than 35 kg at the first slaughter date to have easily grown to over 40 kg prior to the second slaughter date. Therefore, not comparing animals across the same liveweight or live weight range. To overcome this, lambs were compared at the same carcass weight by fitting carcass weight as a covariate to carcass and meat quality characteristics.

In addition, the trial design did not include a treatment group investigating early weaning onto perennial ryegrass-white clover pasture for a balanced comparison against early weaning onto a plantain-clover mix. This did not allow for a complete comparison of the effects of early weaning or forage treatments. Future research would ideally compare weaning lambs early on a plantain-clover mix and perennial ryegrass-white clover pasture to investigate if lambs could be weaned onto pasture instead of a high nutritive forage crop and reach a minimum slaughter weight >35 kg and the effect on carcass characteristics and meat quality.

After the treatment period lambs were finished on perennial ryegrass-white clover pasture to ensure a minimum set live weight was achieved at slaughter. Lambs were finished on perennial ryegrass-white clover pasture which is different to a plantain-clover mix. This could have diluted some of the forage treatment effects on the carcass characteristics and meat quality of lamb. Perennial ryegrass has a lower feeding value than a plantain-clover mix which could have influenced lamb growth and subsequently carcass weight and composition. To fully investigate the treatment effects, it would be ideal for the lambs to graze treatments for a longer period and analyse carcass and meat quality characteristics directly after the treatment period.

Additional statistical analysis could be done by fitting liveweight or age as a covariate to carcass and meat quality characteristics to control for any differences in live weight or age for the two slaughter groups to investigate the effect of lamb weaning age and forage diet on carcass and meat quality characteristics.

Chapter 7: Conclusion and Recommendations

The study has shown early weaning of lambs onto a plantain-clover mix does not have negative effects on carcass and meat quality. Over the course of the study early weaned lambs (EARLY) grew faster compared to conventionally weaned lambs grazing perennial ryegrass-white clover pasture <1200 kgDM/ha (LOW) but grew at a slower rate compared to conventionally weaned lambs grazing a plantain-clover mix (HERB). The slower growth rate and subsequently lighter carcasses of early weaned and restricted perennial ryegrass pasture raised lambs indicate that a lower nutritive diet as a consequence of the lack of milk intake or using a grass species will mean lambs will need more time to achieve a set finishing weight. The GR fat depth and IMF% did not differ among treatments. Early weaned lambs produced less trimmed fat compared to HIGH and LOW lambs and as a result HERB and EARLY lambs had a lower trimmed fat% compared to HIGH lambs. Correspondingly, lambs in the EARLY treatment have a higher muscle% compared to HIGH lambs, with intermediate values produced by HERB and LOW lambs. The difference in muscle% was not large enough to cause a variation in commercially measured (VIAscan) lean meat yield of the carcass. Given the higher muscle% of EARLY lambs compared to HIGH lambs it is likely that lambs weaned at eight weeks of age onto plantain-clover produce a greater amount of saleable meat compared to lambs weaned at 14 weeks of age grazing perennial ryegrass-white clover pasture. The GR fat depth and lean meat yield are measures for determining carcass fatness and leanness and subsequently carcass classification. Weaning age and the forage diet had a small effect on carcass composition but is unlikely to influence the fat grade or lean meat yield of the carcass and therefore carcass classification.

Early weaning can provide several benefits on the wider farm system in terms of feed supply. Early weaning removes the lactational demand on the ewe, reducing the amount of feed required to support both ewe and lamb, freeing up herbage allowing the farmer to prioritise the nutrition of both ewe and lamb. Implementing early weaning could provide the opportunity for hogget mating (Beef and Lamb New Zealand, 2017). The additional feed supply could improve hogget body condition prior to mating the following year (Beef and Lamb New Zealand, 2017). Early weaning also allows cull ewes to be sent for slaughter at an earlier date whilst slaughter prices are high, saving additional feed that can be used for ewe conditioning (Cranston *et al.*, 2016). The ultimate pH did not vary among treatments which is likely the reason why there was a lack of difference in other meat quality traits, such as colour, water-holding capacity, and peak shear force between treatments. Some traits, such as sarcomere length and total shear force work, did have a difference, but the difference is unlikely to be large enough to be a sensorial difference observed by consumers indicating that generally the forage diet has no effect on meat quality.

Overall, the weaning age and forage diet has little to no effect on carcass characteristics, carcass composition, and meat quality of lamb when a target slaughter weight was used. In terms of carcass and meat quality early weaning has neither an advantage nor disadvantage over conventional weaning. Early weaning can therefore be considered as a potential farm management option if it has benefits for managing feed resources. To minimise the potential negative effects of early weaning, farmers should implement this strategy under favourable pasture conditions, where lambs are weaned onto a high nutritive forage such as plantain-clover. By implementing early weaning there will be no impact on the carcass and the quality of meat produced therefore, the benefits of early weaning for feeding management can be implemented without concern on the return made on the carcass.

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Chapter 9: Appendices

9.1. Appendix 1: SAS code

```
ods html close;
ods html newfile=none;
dm 'odsresults; clear';
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename Tuapaka dde 'Excel|E:\Tuapaka\[Tuapaka EWL_Primary Data Set_Draft
2 New.xlsx]SAS!R2C1:R87C51';
data Tuapaka;
infile Tuapaka lrecl=6000 dlm='09'x notab dsd missover;
input treat$ CCSID$      sex$ SlaughterWt ADG1 ADG2 ADG3 HW DO VGR LegYld
LoinYld ShldYld TotalYield Leg
Gracilis Sartorius Pectineus Semimembranosus Adductor BicepsFemoris
      Semitendinosus    Quadriceps  Others
Muscularity MB    LMY   Muscle      BoneWt BL Bone FatWt  Fat IMF
SemimembranosusWt TotalTL pH DL24hr DL48hr L a b HA Chroma SL CL PArea
PLoad
run;
proc mixed data=Tuapaka;
 class treat;
 model SlaughterWt = treat /*SlaughterAge SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model ADG1 = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model ADG2 = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model ADG3 = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model HW = treat /*NS covariates: SlaughterAge SlaughterAge*treat*/
/solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model DO = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
```

```
proc mixed data=Tuapaka;
 class treat;
 model VGR = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model LegYld = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model LoinYld = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model ShldYld = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model TotalYield = treat / solution ;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Leg = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Gracilis = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Sartorius = treat /*NS covariates: HW HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Pectineus = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
```

```
 model Semimembranosus = treat HW /*NS covariates: HW*treat and
SlaughterAge SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Adductor = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model BicepsFemoris = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Semitendinosus = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Quadriceps = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Others = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Muscularity = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model MB = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model LMY = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
```

```
proc mixed data=Tuapaka;
 class treat;
 model Muscle = treat HW HW*treat/*NS covariates: SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model BoneWt = treat HW HW*treat/*NS covariates: HW HW*treat and
SlaughterAge SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model BL = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Bone = treat HW /*NS covariates: HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model FatWt = treat HW HW*treat/*NS covariates: HW HW*treat and
SlaughterAge SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Fat = treat HW HW*treat/*NS covariates: HW HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model IMF = treat /*NS covariates: HW HW*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model TL1 = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
proc mixed data=Tuapaka;
 class treat;
 model TL2 = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
```

```
proc mixed data=Tuapaka;
 class treat;
 model TotalTL = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model pH = treat /*SlaughterAge SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model DL24hr = treat pH /*NS covariates: pH*treat or SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model DL48hr = treat pH /*NS covariates: pH*treat or SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model L = treat pH /*NS covariates: pH*treat or SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model a = treat pH /*NS covariates: pH*treat or SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model b = treat pH /*NS covariates: pH*treat or SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model HA = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model Chroma = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
```

```
quit;
proc mixed data=Tuapaka;
 class treat;
 model SL = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model CL = treat /*NS covariates: pH pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model PArea = treat pH pH*treat /*SlaughterAge SlaughterAge*treat*/
/solution;
 LSMeans treat / pdiff ;
run;
quit;
proc mixed data=Tuapaka;
 class treat;
 model PLoad = treat pH /*NS covariates: pH*treat and SlaughterAge
SlaughterAge*treat*/ /solution;
 LSMeans treat / pdiff ;
run;
quit;
```