Effects of early weaning onto herb-clover mix on lamb carcass and meat quality characteristics

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Abstract

After eight weeks of age, the lambs' diet consists of only a small proportion of milk. Early weaning at 8-weeks of age onto high nutritive value forage crops, therefore, may be able to compensate for the removal of milk from the diet whilst maintaining lamb liveweight gains. It is crucial, however, to ensure there are no negative effects of early weaning on the yield of saleable meat and its quality. This study aimed to understand the effects of early weaning onto a herb-mix on carcass and meat quality characteristics.

Ewes and their twin lambs (weighing at least 16kg) were allocated to one of three treatments: 1. Lambs with dams on grass (GRASS) (lambs; n=50; $\bar{x}$ LW=17.0kg), 2. Lambs with dams on herb-mixes (HERB) (lambs; n=50; $\bar{x}$ LW=17.2kg), 3. Lambs weaned onto herb-mixes (56-days old) and dams on grass (EARLY) (lambs; n=50; $\bar{x}$ LW=16.4kg). At 12 weeks of age, all lambs were weaned and lambs with a liveweight of greater than 35kg were sent for slaughter (n=28; $\bar{x}$ LW=36.9kg). The remaining lambs grazed together on ryegrass-based pasture for six weeks. After this period, lambs with a liveweight >35kg were sent for slaughter (n=93; $\bar{x}$ LW=40.4). Hot-carcass weight and VIAscan estimates of GR soft tissue depth (tissue depth 110 mm from the midline on the 12th rib) and lean meat yields were obtained. Meat quality assessments were conducted to obtain pH, colour, water-holding capacity, intramuscular fat, sarcomere length and tenderness values.

The average daily gain of lambs in the HERB treatment (307.0 $\pm$ 7.4g) were greater than those in the EARLY (255.8 $\pm$ 8.0g) and GRASS (267.8 $\pm$ 8.5g) treatments ($P<0.05$). The dressing out and lean meat yield did not differ among lambs of different treatments ($P>0.05$). The lambs in HERB treatment had greatest hot-carcass weight (17.4 $\pm$ 0.23kg) and GR soft tissue depth (8.2 $\pm$ 0.41mm) ($P<0.05$). The higher average daily gains, carcass weight and GR soft tissue depth of lambs on herb-mix is expected as it has a higher feeding value. Lambs in EARLY treatment had the greatest bone weight ($P<0.05$). Dissected fat weight, muscle-to-bone ratio and muscularity index was greatest in lambs from the HERB treatment ($P<0.05$). There was no difference across the treatments for intramuscular fat percentage, meat colour, drip loss, sarcomere length and shear force values ($P>0.05$). All treatments were associated with low shear

force values (<5kg F). The results suggest that, when taken to a set weight, early weaning of lambs onto herb-clover mix did not appear to have any negative effects on carcass and meat quality characteristics. However, a smaller proportion of early weaned lambs may achieve a set slaughter weight at a set date compared to similar lambs with their dams on a high nutritive value forage. Early weaned lambs are likely to require more time for finishing to a set weight .

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Chapter 1: Literature Review

New Zealand is widely recognized as a world leader in pastoral agriculture (Morris, 2009) and the agricultural sector contributes to a large portion of the export industry's income at 59.6% in 2017 (Beef and Lamb New Zealand, 2018). Sheep farmers are therefore required to consistently produce high-quality products from pastoral production systems to meet export demands. Extensive pastoral production tests farmers' ability to overcome challenges from climate and seasonality effects on production and feed supply which requires detailed planning.

1.1 Early weaning of lambs

In New Zealand, the majority of lambs are born during late winter to late spring in order to match lactation to peak pasture growth rates and optimal pasture quality (Valentine and Kemp, 2007). Lambs are commonly weaned between 10-15 weeks of age and have an average live weight of 28-30 kg (Geenty, 2010). Meat breed ewes on New Zealand hill country have milk production that peaks 1-2 weeks after lambing when assessed by milking (Paten *et al.*, 2013, Peterson *et al.*, 2006, Peterson *et al.*, 2005). Fifteen weeks after lambing, milk constitutes only 20% of the diet of lambs (Muir *et al.*, 2000). Suckling lambs increase their herbage intake as they age in order to meet their nutritional requirements for growth and reducing their reliance on milk. The increased herbage intake of lambs can result in lambs competing with their dams for the same feed resources.

Early weaning of lambs between 6 and 9 weeks of age has been reported to be a useful farm management tool when pasture availability is low to prevent feed competition between the ewe and her lamb and as a means to provide focused nutrition to finish lambs (Cranston *et al.*, 2016). Beef + Lamb NZ (2010) suggest that early-weaned lambs should be a minimum of 16kg live weight at weaning. In addition, they should be provided high quality feed to allow adequate nutrition for growth without milk (Rattray *et al.*, 1976, Muir *et al.*, 2000). If lambs are weaned early, ewes can be offered poorer quality pastures, or restricted feed allowance, whilst maintaining their body condition between late spring and early summer (Cranston *et al.*, 2016). Furthermore, if lamb growth rates can be maintained by early weaning on suitable herbages, it also allows for cast-for-age ewes to be sold earlier when their value is greater (Cranston *et al.*, 2016) and allow herbage to be saved.

An additional benefit to weaning lambs early is to allow for ewe hogget breeding. One of the major reasons that NZ farmers do not breed their ewe hoggets (7-9months old) is the perceived detrimental effects on hogget body condition score and live weight after lambing, resulting in reduced lifetime reproductive performance (Kenyon *et al.*, 2004, Kenyon *et al.*, 2008). Geenty and Sykes (1981) concluded that early weaning of lambs and diverting highly digestible herbage to the lamb and not the ewe improves energetic efficiency of lamb growth and allows for ewe hoggets to achieve greater live weights and body condition score prior to mating.

1.2 Carcass characteristics

The ability to accurately measure carcass characteristics is important for performance testing, grading/assigning a value or payment of meat producing animals (Purchas *et al.*, 1989). The carcass characteristics that will be discussed in this section are carcass weight and dressing-out percentage, carcass composition, tissue distribution, carcass shape and muscularity.

1.2.1 Carcass weight and Dressing-out percent (DO %)

The term "carcass" is defined as the part of the animal remaining after normal commercial dressing procedures (Purchas *et al.*, 1989). The dressing-out percent is the proportion of the live weight of the lamb that is made up of carcass and allows for the prediction of the carcass weight of an animal with a known live weight(Purchas *et al.*, 1989). In New Zealand, production systems utilise an estimated DO% to establish carcass weights because prices received are based on per kilogram of carcass. The carcass weight is a reflection of the body growth attained by the animal up until slaughter (Purchas *et al.*, 1989). In addition, in New Zealand prices change markedly between different carcass weight categories used for classification (Schreurs, 2012). Equation 1 shows the relationship between carcass weight, live weight and DO%.

Equation 1:

$$Carcass\ weight\ (kg) = Live\ weight\ (kg) \times DO\%$$

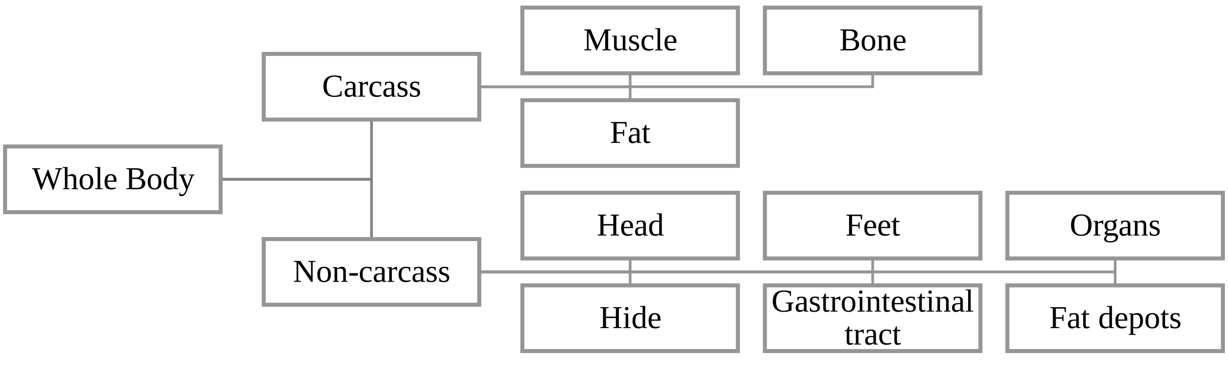
The DO% is highly dependent on the conditions under which the live weight and carcass weight measurements were made and differences in carcass dressing procedures (Litherland *et al.*, 2010). The live weight of an animal prior slaughter is subject to variation primarily due to gut fill at the time of weighing (Purchas *et al.*, 1989). Gut fill is affected by the digestibility of feeds as highly digestible feed lead to lower gut fill due to increased rumen outflow (Litherland *et al.*, 2010). Differences in carcass dressing procedures are usually related to the extent to which carcass is trimmed prior to weighing (Purchas *et al.*, 1989). The gender of lamb can also affect DO% as entire males have a higher proportion of non-carcass components (i.e. the testes) that makes up a proportion of their live weight (Litherland *et al.*, 2010).

Differences in muscling, fatness and fleece weights among breeds can also influence DO% (Johnson *et al.*, 2005b). The DO% values are usually greater for heavier animals because this represents the carcass tissues (muscle, fat and bone) that have grown more rapidly than non-carcass tissues on a proportional basis.

1.2.2 Carcass composition

Carcass composition considers the contribution of muscle, fat and bone to carcass weight (Purchas *et al.*, 1989). Carcass composition can be divided into chemical or physical components. The former measures components using chemical methods to give protein and fat values and the latter involves the separation of components by dissection. In this thesis, we will refer to carcass composition in terms of physical components (Figure 1-1).

Figure 1-1 Physical or anatomical components of carcass composition.



Standard methods of assessing the composition of a whole body or a carcass is by physical dissection into muscle, fat and bone and then weighing the components (Purchas *et al.*, 1989). A sample cut, for example, the hind leg, is usually used for assessment and the results are used to extrapolate the composition of the whole carcass (Purchas *et al.*, 1989). Once the carcass has been dissected into its fat, muscle and bone components, the information is usually presented in alternative forms including the muscle-to-bone ratio (M:B), muscle percentage, and fat percentage.

1.2.2.1 Muscle to bone ratio

The muscle to bone ratio (M:B) takes into account the weight of the bone and the weight of the muscles adjacent to the bone(Purchas *et al.*, 1989). Muscle to bone ratio is an objective measurement and an increase in M:B is often associated with superior muscularity (Purchas *et al.*, 1991b). Muscularity, however, is dependent on bone length. As a result, the positive relationship between M:B and muscularity only holds true when comparing animals with similar bone lengths (see Section 1.2.4) (Purchas *et al.*, 1991b).

A greater M:B can be due to a lower bone weight per unit length rather than heavier muscles causing animals of the same muscularity to have large differences in M:B (Abdullah *et al.*, 1993). An example is ram lambs with poorer M:B compared to ewe lambs despite having similar muscle depths because the ram lambs have a heavier bone structure (Purchas *et al.*, 1991b).

1.2.2.2 Fat Percentage

Adipose tissue is a late developing tissue compared to muscle and bone (Purchas *et al.*, 1989). Carcass fat is valuable as it contributes to carcass weight during animal growth (Purchas *et al.*, 1989). Fat is deposited in three carcass depots – subcutaneous, intermuscular (between the muscles) and intramuscular (within the muscles)(Warris, 2010).

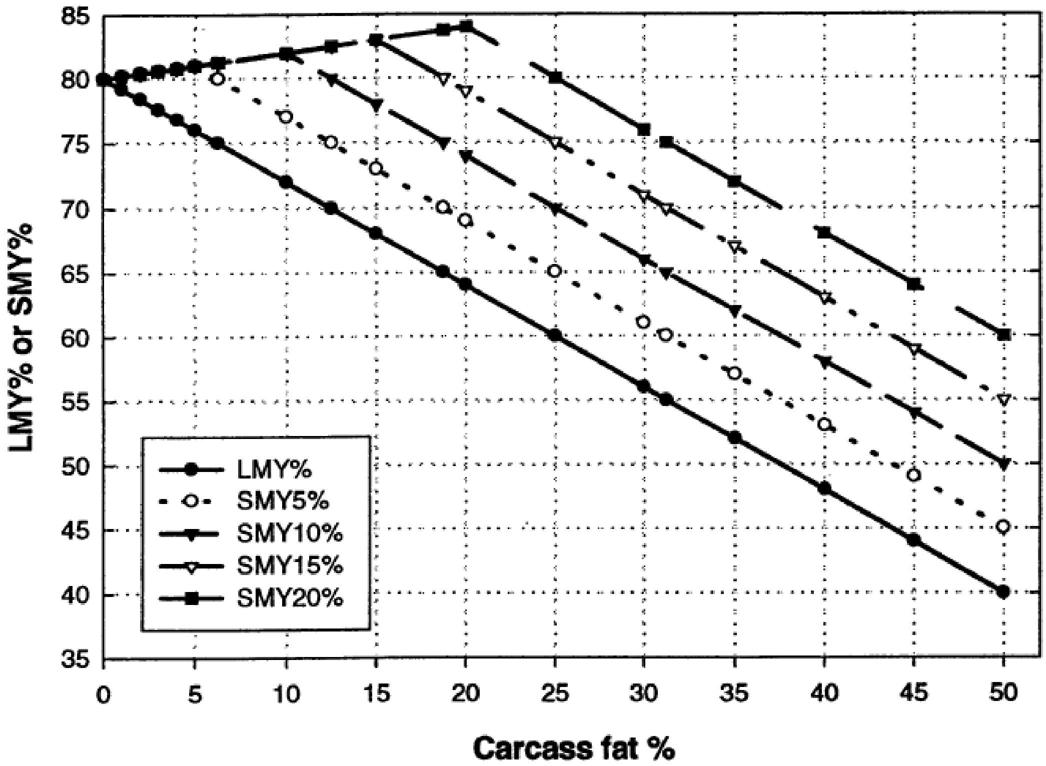
An increase in carcass subcutaneous fat, however, causes a slower carcass cooling rate after slaughter, allowing rigor to be obtained at higher temperature, and a more rapid decline in pH which can influence meat colour (Priolo *et al.*, 2001). Selection for very low subcutaneous fat can increase likelihood of cold shortening of carcasses due to lack of insulation (Smith *et al.*, 1976). Low fat cover in light weight lambs was associated with tougher meat and lower flavour intensity than lambs with higher fat cover (Sañudo *et al.*, 2000). In addition to cold shortening, carcasses with very little subcutaneous fat may lack sufficient fat for satisfactory palatability (Kerr, 2000).

1.2.2.3 Muscle percentage, lean meat yield and saleable meat yield

Both lean meat yield (LMY) and saleable meat yield (SMY) are expressed as a percentage of carcass weight. Lean meat yield excludes all visible fat (except intramuscular fat), and is therefore synonymous with the muscle percentage (Purchas *et al.*, 1989). Saleable meat yield allows for a variable amount of fat on the meat depending on the specifications required for different markets.

The relationship between SMY% for carcasses of different fat percentages are shown in Figure 1-2. Saleable meat yield declines when the carcass fat percentage is above the allowable percentage. For example, when the saleable meat allows for 20% fat, SMY% increases as carcass fat% increases up until 20% and thereafter declines after that as the excess fat must be trimmed. Lean meat yield relationship is shown when there is zero allowable fat.

Figure 1-2 Changes in carcass meat yield with increasing fat percent (reproduced from (Hui and Aalhus, 2012).



Lean meat yield is also affected by trimmed fat percent and M:B (Abdullah *et al.*, 1993). The value of a carcass is determined by the LMY% which can be determined by Fat% and M:B (Purchas *et al.*, 2002); Equation 2). LMY% is proportion of muscle in the carcass, therefore as the fat percentage increases, LMY% decreases and vice versa.

Equation 2:

$$LMY\% = (100 - Fat\%) \times \frac{M:B}{M:B + 1}$$

As illustrated in Equation 2 and Figure 1-2, a decrease in fat% and an increase in M:B increases LMY% (Purchas, 2012, Purchas *et al.*, 2002). With other things being equal, an increase in bone weight would decrease LMY% because an increase in bone weight decreases the M:B. An increase in muscularity would indicate an increase in LMY% because a well-muscled animal would have more meat (muscle).

1.2.2.4 Indirect measures of carcass composition for carcass classification

There are many indirect methods of estimating aspects of the composition of carcasses. Physical dissection of a sample cut can be used to estimate the composition of the whole carcass (Hui and Aalhus, 2012). Besides that, a direct measurement after making a small incision where the GR measurements are made (110 mm from the midline on the 12th rib) can be used to indicate percent lean meat or percent fat in animal carcasses (Purchas *et al.*, 1989). Recent trends in carcass evaluation techniques include scanning instruments such as the computer aided tomography (CT) and magnetic resonance imaging (MRI) scanners, video image analysis (VIA) and electromagnetic scanning by measuring total body electrical conductivity (TOBEC) (Gupta *et al.*, 2013).

In New Zealand, carcasses are graded based on different levels of GR soft tissue, which then affects the payments received by the farmers. When comparing within a set weight class, for example class L (9.1-13.2 kg), a low fat depth of up to 6mm (class Y), medium fat depth of up to 12mm (class P), high fat depth of up to 15mm (class T) and excessive fat depth of over 15mm (class F) would negatively impact the price schedule of the carcasses. Class Y and P are more desirable and are considered export classes whereas class T and F would require trimming of excessive fat prior to export and are less desirable (New Zealand Meat Classification Authority, 2004).

1.2.3 Tissue Distribution

The distribution of muscle and fat holds economic interest. Muscle and fat distribution is important because they indicate the efficacy of production and also for meeting requirements of markets where different carcass attributes are considered desirable for eating quality (i.e. marbling) (Macfarlane *et al.*, 2009).

1.2.3.1 Fat Distribution

Fat distribution considers how fat is partitioned between different carcass depots and within a depot relative to the total fat or to carcass weight (Purchas *et al.*, 1989). Fat distribution is important from a commercial point of view as the partitioning of fat between the carcass and non-carcass depots can affect DO%. In addition, if more fat is partitioned to the subcutaneous fat depot, then cut-off fat depths used in carcass classification will be reached at lower levels of overall carcass fat percent. An increase in subcutaneous fat can decrease DO% depending on market requirements as excess fat is trimmed and removed (Hui and Aalhus, 2012). When more fat is partitioned to the intramuscular fat depot, this is desirable for achieving greater marbling scores (Macfarlane *et al.*, 2009). Fat partitioning to intramuscular depots is also important as a 5% minimum intramuscular fat is required for acceptable meat quality such as juiciness, tenderness, flavour, appearance as well as nutritional value (Hopkins *et al.*, 2006, Lambe *et al.*, 2008, Macfarlane *et al.*, 2009, Young *et al.*, 2009).

1.2.3.2 Muscle Distribution

Muscle distribution is expressed in terms of the weight of individual muscles or group of muscles relative to the weight of total muscle or carcass weight (Purchas *et al.*, 1989). Muscle distribution is important from a commercial stand point because cuts from different parts of the carcass have different retail value (Purchas *et al.*, 1989). Cuts at the proximal hind limb and around the spinal column generally have a much greater value compared to the abdominal or distal fore limb cuts (Butterfield, 1988). As a result, meat yield in these areas is an important component of most sheep breeding programmes.

LoinMAX™ and MyoMAX™ are two commercial DNA tests that are commonly used to assist in the selection of sheep for superior meat yield. LoinMAX™ is a test for a quantitative trait locus (QTL) on sheep chromosome 18 that affects rib-eye (Longissimus dorsi) muscling. Sheep carrying this QTL have an increase of approximately 11% and 8% in rib-eye muscle area and weight respectively, allowing for greater profit from this high-priced cut (Nicoll *et al.*, 1998, Campbell and McLaren, 2007). Sheep carrying the MyoMAX™ QTL have increased leg muscle and decreased leg fat (Johnson, 2003, Johnson *et al.*, 2005a).

1.2.3.3 Bone Distribution

Bone distribution is expressed in terms of the weight of individual bones, or group of bones, relative to the total bone weight (Purchas *et al.*, 1989). Bone distribution has less commercial significance because it is usually removed unless sold as part of a cut (Purchas *et al.*, 1989). Bone growth, however, is important for animal development because the bones acts as a framework for muscular contraction to allow for locomotion, protection of internal organs and, production of blood cells(Purchas *et al.*, 1989). Hence, bone growth occurs early in sheep with those bones used for locomotion developing first in early life.

1.2.4 Carcass Shape and Muscularity

Carcass shape, or conformation, is expressed in terms of the thickness of muscle plus fat relative to a skeletal dimension e.g. the length of a bone (Purchas *et al.*, 1989). It represents a subjective assessment of the shape of an animal or carcass, and depends on the quantity and distribution of muscle and fat, skeletal dimensions and M:B ratio (Wolf *et al.*, 2006). Muscularity on the other hand describes only the thickness of a muscle relative to a skeletal dimension (Purchas *et al.*, 1989). Carcass shape has been used to score and grade carcasses as it is considered that carcasses with more musculature will provide a greater LMY% (Fisher *et al.*, 2003). Due to greater muscularity being associated with deep muscles, it is usually synonymous with more muscle and hence a greater M:B ratio (Abdullah *et al.*, 1998, Purchas *et al.*, 2002, Purchas, 2012).

It was proposed by Purchas *et al.* (1991b) that muscularity could be estimated using Equation 3 which describes the depth of the muscle (often described by weight) relative to the dimension of the bone (e.g. bone length) whereas M:B ratio describes the ratio of muscle weight and bone weight from the measured part (Johnson *et al.*, 2005b). Other methods to estimate muscularity include the use of CT in the assessment of muscularity of the leg and loin in lambs (Jones *et al.*, 2004, Navajas *et al.*, 2007, Navajas *et al.*, 2008, Lambe *et al.*, 2009).

Equation 3:

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

1.3 Meat Quality Characteristics

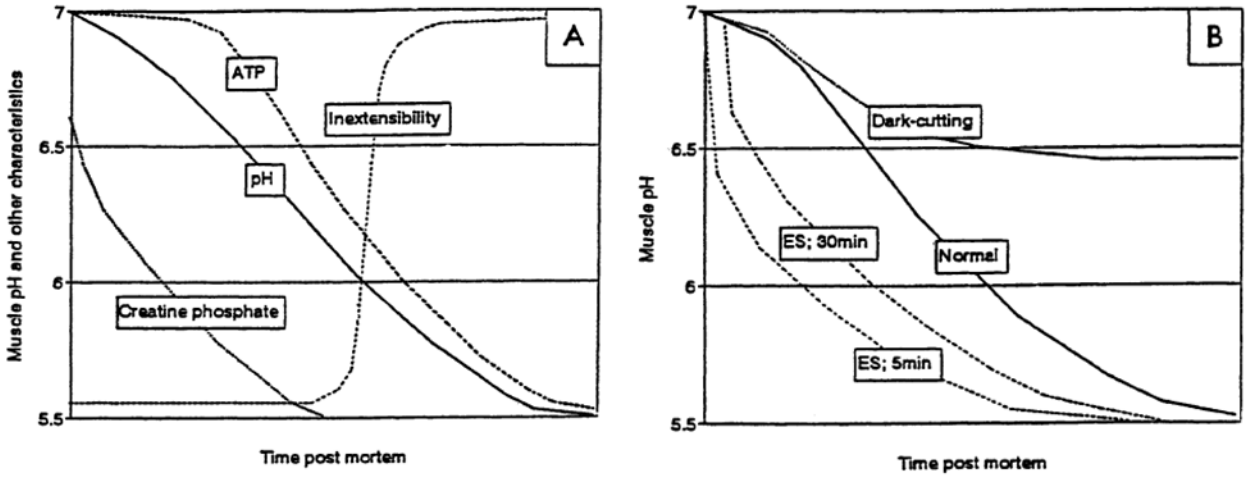
Consumer perception of meat quality is driven by the eating experience and is usually related to appearance and palatability (Troy and Kerry, 2010). In addition, knowledge of background characteristics also effect perception (e.g. health benefits)(Wood, 2017). Consumer perceived qualities have direct effects on the price that they are willing to pay and repurchasing decisions. Consumer perceptions are not fixed and may change due to complex psychological factors (Köster and Mojet, 2007). The meat quality characteristics that will be discussed in this literature review are pH, appearance, tenderness, and water holding capacity.

1.3.1 Meat pH

Although pH is not a meat quality attribute that can be directly detected by consumers, it contributes to many aspects of meat quality (Purchas *et al.*, 1989). A high ultimate pH (above 6) is associated with decreased flavour strength, darker colour, accelerated meat spoilage and decreased tenderness and juiciness (Lawrie, 1991, Newton and Gill, 1981, Purchas *et al.*, 1989). Since pH is a driver of many appearance and palatability characteristics, it is hence considered here as a meat quality characteristic.

After slaughter, oxygen and nutrient supply to muscles is stopped and cells are forced to undergo glycolytic metabolism using stored glycogen to provide energy for cell metabolism (Hui and Aalhus, 2012, Purchas *et al.*, 1989). Lactic acid begins to accumulate, as a by-product of glycolytic metabolism, causing a decline in muscle pH (Figure 1-3 A)(Warris, 2010). When glycogen stores are depleted, or when pH has dropped to a level where glycolytic pathway enzymes are unable to function, ATP is depleted and the muscle is said to be in a state of rigor mortis (Purchas *et al.*, 1989). A decrease in glycogen concentration in the muscle at the time of slaughter results in a higher ultimate pH value leading to darker cutting meat (Figure 1-3 B)(Aberle *et al.*, 2001, Purchas *et al.*, 1989).

Figure 1-3 Post mortem changes in muscle up to rigor mortis. (ES; electrical stimulation)(Adapted from (Aberle *et al.*, 2001) and (Warris, 2010).



1.3.1.1 Objective Measurements

pH is usually measured objectively using a pH meter probe and the ultimate pH is usually measured at any time after 24 hours post mortem (Purchas *et al.*, 1989, Warris, 2010). Subjective measurements for pH do not exist.

1.3.2 Meat Appearance

Appearance characteristics provide meat quality cues for the consumer at the point of purchase (Purchas *et al.*, 1989). Consumers usually associate a brighter red with freshness and the colour is mainly determined by the colour pigments within the muscle fibres, the amount of intramuscular fat and connective tissue present (Pethick *et al.*, 2005b, Purchas *et al.*, 1989). An increase in intramuscular fat can also contribute to the appearance of a lighter coloured meat as found in animals raised in different production systems, i.e. intensive indoor farming systems (Priolo *et al.*, 2001).

The oxidation and reduction of myoglobin (colour pigment) present in meat also influences meat colour. Before meat is exposed to air, deoxymyoglobin (reduced myoglobin) results in the purple-red colour of meat (Faustman and Suman, 2017). Oxymyoglobin forms after exposing deoxymyoglobin to oxygen resulting in a bright red pigment (Faustman and Suman, 2017) that consumers associate with freshness. Oxymyoglobin readily oxidises to metmyoglobin which results in a brown colour which consumers associate with prolonged time since being package, a lack of freshness and poor eating attributes (Troy and Kerry, 2010).

1.3.2.1 Objective Measurements

Meat colour is usually measured objectively using a Chroma meter using the readings L*, a*, and b* scale (where L* measures relative lightness, a* relative redness, b* relative yellowness). The rate of colour deterioration under storage conditions can be tested with repeated measures to determine the potential shelf life that consumers associate with freshness (Faustman and Suman, 2017).

1.3.2.2 Subjective Measurements

Consumer evaluation and panellist assessment can be used to assess visual acceptability of meat colour. In a consumer evaluation analysis, a large sample size is needed (40-50 consumers minimum) and they either participate in a group discussion or are interviewed individually (Meilgaard *et al.*, 2016). In a trained panellist assessment, colour is measured, analysed and interpreted through the individual's senses. The sample size needed is smaller than consumer evaluations (5-7 trained panellist minimum)(Meilgaard *et al.*, 2016). The measurements of colour from trained panellists depends on their ability describe the colour accurately (Meilgaard *et al.*, 2016).

Subjective tests of meat colour are usually not carried out because the results are greatly affected by lighting, visual deficiencies of the eye and most importantly the difference in perception of colour in individuals (Luciano *et al.*, 2009, Young *et al.*, 2009). It has been found, however, that b* (yellowness) values were positively related to sensory appreciation of meat colour degradation, and a* (redness) values were negatively correlated to the sensory evaluation of discolouration (Luciano *et al.*, 2009).

1.3.3 Meat Tenderness

Meat tenderness is one of the more important eating characteristics that consumers associate with their eating experience (Hopkins, 2017). The structural components, pH and extent of post mortem proteolysis in meat define the intrinsic tenderness of meat. The structural components includes the connective tissues , the contractile component, which is the muscle filaments , and the intramuscular fat (Purchas *et al.*, 1989). Muscle filaments consist of myofibril which is made up of a number of proteins including actin, myosin, troponin, tropomyosin, C-protein, titin and nebulin (Kemp *et al.*, 2010a). The proteolysis of these proteins contributes to ageing of meat (see Section 1.3.3.1).

The presence intramuscular fat can also affect meat tenderness by a dilution effect. Muscle fibres and connective tissues are strong structural components compared to intramuscular fat, therefore, an increase in intramuscular fat will reduce the overall work needed to shear through meat (Hopkins *et al.*, 2006). The presence of intramuscular fat also induces saliva production during chewing giving the perception of increased tenderness during eating (Hopkins *et al.*, 2006, Thompson, 2004). An increase in subcutaneous fat has been correlated to an increase in intramuscular fat in the loin (McPhee *et al.*, 2008), thereby contributing to the differences in shear force (Campbell *et al.*, 2011, Schreurs *et al.*, 2013). An increase in subcutaneous fat will also prevent cold-shortening and toughening and increase the rate at which proteolysis occurs (Purchas *et al.*, 1989). Although there are multiple factors that can affect tenderness, ageing (see Section 1.3.3.1) and pH are the key contributors alongside composition and structural characteristics of the muscle.

The amount of connective tissues present in the muscle and solubility of collagen also affect tenderness (Hopkins, 2017). The main fibrous connective tissue present in the muscles is collagen (Hopkins, 2017, Purchas *et al.*, 1989). Generally an increase in the concentration of collagen is associated with a decrease in meat tenderness (other things being equal)(Purchas *et al.*, 1989). When collagen is heated, it changes from a fibrous to a soluble protein (gelatin)(Purchas *et al.*, 1989). The solubility of collagen is determined by the amount of collagen crosslinks present (Hopkins, 2017). An increase in the amount of collagen crosslinks would require an increased amount of heat to achieve solubilisation of collagen (Purchas *et al.*, 1989). Collagen from very young animals has relatively few crosslinks and therefore has increased tenderness (Hopkins, 2017). Young *et al.* (1993) demonstrated a reduction in collagen solubility as an animal ages and an increase in shear force. This is also consistent with Hopkins *et al.* (2007)

who reported a higher shear force value for meat from sheep aged 14-20 months compared to those aged 8-14 months.

1.3.3.1 Ageing effects on tenderness

Figure 1-4. Major components of the sarcomere(reproduced from (Kemp *et al.*, 2010a).

Ageing is proteolysis that occurs post mortem (Hopkins and Thompson, 2001). During post mortem tenderisation, the major changes in the myofibrillar structure are due to the proteolysis of key myofibrillar proteins such as, desmin, titin, z-disks and costameres which maintain the structure of myofibrils (Koohmaraie, 1996, Kemp *et al.*, 2010a, Koohmaraie and Geesink, 2006; Figure 1-4)

The extent of muscle protein proteolysis is a significant determinant of ultimate tenderness of meat (Kemp *et al.*, 2010a). The proteolytic enzymes that are responsible for protein proteolysis are extensively described in Kemp *et al.* (2010a) and Matarneh *et al.* (2017). The main endogenous protease responsible for proteolysis with meat aging is the calpain family of enzymes (calcium-activated cysteine proteases) (Dransfield, 1994, Koohmaraie and Geesink, 2006, Huff Lonergan *et al.*, 2010, Kemp *et al.*, 2010a). There are several other proteolytic enzymes that also contribute to meat tenderisation, e.g. caspase. These enzymes work optimally at different pH ranges providing a synergistic effect post mortem (Pearce *et al.*, 2011, Ouali *et al.*, 2006).

1.3.3.2 pH Effects on tenderness

The relationship between tenderness and ultimate pH is curvilinear with highest shear force values observed at an ultimate pH between 5.8 – 6.2 (Hopkins, 2017, Devine *et al.*, 1993); Figure 1-5). Although a high ultimate pH results in meat that has lower shear force, it often produces dark and dry cuts that are undesirable to consumers. To maximise tenderness, pH should be below pH 5.8.

Figure 1-5 The relationship between ultimate pH and shear force of the lamb longissimus dorsi muscles (Reproduced from (Devine *et al.*, 1993).

1.3.3.3 Objective and subjective measurements of tenderness

The Warner-Bratzler shear machine and the MIRINZ tenderometer are used to assess tenderness. The former mimics a shearing action while the later mimics a biting action (Purchas *et al.*, 1989). The threshold for acceptable mean shear force is 78.4 N (8 kgF) using a MIRINZ tenderometer (Frazer, 1997) and this is equivalent to 117.7 N (12kgF) on a Warner-Bratzler shear machine (Johnson *et al.*, 2005b, Peachey *et al.*, 2002).

Although it is common to evaluate meat tenderness objectively to obtain a numerical value, sensory evaluation more accurately reflects the actual eating experience of consumers (de Huidobro *et al.*, 2005). Subjective assessments of lamb tenderness utilise both trained and consumer panels (Meilgaard *et al.*, 2016). It can be difficult, however, for people to differentiate tenderness from juiciness and hence, the term "succulence" is often used for the subjective sensory analysis of lamb (Purchas *et al.*, 1989).

1.3.4 Water holding capacity and Juiciness

Water holding capacity is defined by the ability of meat to bind water and to keep it with the muscle structure (Pearce *et al.*, 2011). Muscles are approximately 75% water and the level of hydration of meat after processing or cooking can affect tenderness and juiciness (Warner, 2017). Measuring juiciness is not an easy task because it is affected by the amount of water in the meat and the amount of saliva produced during eating when testing subjectively (Purchas *et al.*, 1989). The level of intramuscular fat interacts with the sensory assessment of juiciness by stimulating salivation during chewing, thus giving the perception of juiciness (Thompson, 2004).

Water loss occurs due to myofibril shrinkage during the pre-rigor pH fall, where myosin heads attach to the actin filaments forming inextensible actomyosin complex resulting in reduced space for water to reside between the myofilaments (Pearce *et al.*, 2011, Warner, 2017). The water appears as drip or purge on the surface of the meat (Hughes *et al.*, 2014).

Proteolysis can improve water-holding capacity by creating a "sponge effect" between muscle filament and myofibrils (Xiong, 2004, Zhang *et al.*, 2006, Zeng *et al.*, 2017). Extended proteolysis, however, reduces water-holding capacity due to degradation of muscle fibre structure (Xiong, 2004, Pearce *et al.*, 2011). An inevitable consequence of aging, especially with dry aging, is drip loss and evaporation (Rosenvold *et al.*, 2008).

Water loss is associated with decreased storage life of the meat as it increases the amount of free water available for microbial proliferation and hence, spoilage (Kerry and Tyuftin, 2017). It is also associated with weight loss and a poor overall consumer reaction when meat is sitting in liquid (purge) in its packaging (Purchas *et al.*, 1989, Zagorec and Champomier-Vergès, 2017).

1.3.4.1 Objective and subjective measurements of juiciness

Ability of a muscle hold moisture can be assessed by measuring the purge loss of a piece of meat by hanging for 1-2 days and reweighing (Warner, 2017). Water holding capacity can also be measured by pressing a piece of meat between filter paper and expressing it as the ratio of wetted area to muscle area (Warner, 2017). Likewise, water holding capacity can be measured from water loss during thawing and during cooking (Warner, 2017). Water holding capacity is usually affected by post-slaughter processes such as the rate of chilling and pH (Schreurs *et al.*, 2013). If carcasses of lambs grazing different forage treatments were handled the same, it is unlikely that major differences in water holding capacity of meat would be observed (Schreurs *et al.*, 2013). Moisture can also be lost through the cooking process and this is termed 'cooking loss'.

Sensory analysis can be carried out to assess the juiciness of meat. Increased marbling has a positive effect on saliva production causing the perception of increased juiciness during eating (Thompson, 2004). Studies have found, however, that there is no or little difference in juiciness between the meat of lambs grazing different forage treatments when testing with subjective tests (Campbell *et al.*, 2011, Fraser *et al.*, 2004)

1.4 Traditional and Alternative Forages in New Zealand

Perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pastures are the predominant pastures in New Zealand. There has been recent interest, however, in the use of alternative forages such as plantain, chicory, red clover and white clover for finishing lambs.

1.4.1 Traditional perennial ryegrass/white clover pasture

Figure 1-6 Perennial Ryegrass (*Lolium perenne)*

The most common pasture in New Zealand is a mix of perennial ryegrass and white clover (Easton, 1999). This traditional pasture mix has low maintenance costs and is well adapted to the weather conditions (Burke *et al.*, 2002). The annual production of ryegrass white clover pasture has been reported to be an average of 15 tonnes DM per ha (Clark *et al.*, 2001).

Perennial ryegrass is a seasonal pasture with maximum production and quality during spring and early summer (Matthews *et al.*, 1999). Dry weather conditions reduces productivity and quality of perennial ryegrass and thus has a negative effect on animal growth (Powell *et al.*, 2007). Crude protein (CP) levels ranges between 15-26%; neutral detergent fibre (NDF) between 35-55%; acid detergent fibre (ADF) between 20-31% and metabolisable energy (ME) between 9.0-11.4 MJ/kg DM depending on the season, maturity and management practices (Somasiri, 2014;Table 1-1)

Table 1-1 Summary of nutritional comparisons of different forages (Perennial ryegrass, Plantain, Chicory, White clover and Red clover) in New Zealand (Somasiri, 2014, Burke *et al.*, 2000, Hayes *et al.*, 2010, Barry, 1998, Fulkerson *et al.*, 2007, Lindsay *et al.*, 2007, Kemp *et al.*, 2010b)

Forage	Perennial Ryegrass	Plantain	Chicory	White Clover	Red Clover
CP (% DM)	15-20	13-25	11-24	24-30	22-30
NDF (% DM)	35-48	29-37	13-38	26-34	34-41
ADF (% DM)	20	24	22	19-23	25-38
ME (MJ/kg DM)	9-11	11-13	7-14	9-12	9-13

1.4.2 Plantain (*Plantago lanceolata*)

Figure 1-7 Plantain (*Plantago lanceolata*)

Plantain is a perennial herb with a taproot, many vegetative shoots and is well adapted to tolerate dry summer conditions (Kemp *et al.*, 1999, Stewart, 1996). The annual production of plantain has been reported to be around 17 tonnes DM per ha (Powell *et al.*, 2007).

Plantain has been reported have a high concentration of minerals such as calcium, magnesium, sodium, phosphorus, zinc, copper and cobalt (Stewart, 1996). Plantain has a crude protein (CP) of 13-25%, neutral detergent fibre (NDF) of 29-37%, acid detergent fibre (ADF) of 24% and metabolisable energy (ME) of 11 to 13 MJ per kg DM (Burke *et al.*, 2000, Hayes *et al.*, 2010, Somasiri, 2014);Table 1-1). Grazing plantain results in greater liveweight gains (222g/day) when there is more vegetative leaf offered (Moorehead *et al.*, 2002) while liveweight gains will be 84-141g/day when there is a greater percentage of seed heads offered (Somasiri, 2014).

1.4.3 Chicory (*Cichorium intybus*)

Figure 1-8 Chicory (*Cichorium intybus*)

Chicory is a perennial herb with a taproot, leafy stems and flowers during summer (Rumball, 1986). It grows well during late spring and early summer with an annual production of 9 to 14 tonnes DM/ha (Li and Kemp, 2005, Powell *et al.*, 2007). Chicory is highly digestible and highly palatable allowing for high intakes resulting in for positive impacts on lamb growth (Athanasiadou *et al.*, 2007, Marley *et al.*, 2005).

Chicory has been reported to have a CP concentration of 11-24%, NDF of 13-38%, ADF of 22% and ME ranging between 7 to 14 MJ per kg DM (Barry, 1998, Burke *et al.*, 2000, Hayes *et al.*, 2010, Somasiri, 2014;Table 1-1). Chicory contains high levels of minerals such as copper and zinc (Li and Kemp, 2005). Lambs fed chicory had growth of between 146-311g per day (Young *et al.*, 1994, Scales *et al.*, 1995, Hopkins *et al.*, 1995a).

1.4.4 White Clover (*Trifolium repens)*

Figure 1-9 White Clover (*Trifolium repens*)

White clover is a stoloniferous plant that favours an optimal growth temperature of 18-30°C thus resulting in maximum production during summer in New Zealand (Valentine and Kemp, 2007). The annual production of white clover ranges from 7 to 10 tonnes per ha (Hyslop, 1999).

White clover has been reported to have a CP concentration of 24-30 %, NDF of 26-34 %, ADF of 19-23 % and a ME of 9 to 12 MJ per kg DM (Burke *et al.*, 2000, Fulkerson *et al.*, 2007, Lindsay *et al.*, 2007;Table 1-1). Weaned lambs grazing white clover swards have been reported to have liveweight gains of between 201 to 320 g per day (Cruickshank *et al.*, 1985, Fraser and Rowarth, 1996, Scales, 1993).

1.4.5 Red Clover (*Trifolium pretense*)

Figure 1-10 Red clover (*Trifolium pratense*)

Red clover is a perennial plant that has a taproot that grows deep into soil levels with its main axis above ground which develops branches and true leaves (Frame *et al.*, 1998). As seen in white clover, red clover's maximum production occurs during the summer months in New Zealand (Valentine and Kemp, 2007). The annual production of red clover is approximately 11-15 tonnes per ha (Hyslop, 1999).

Red clover has a high ME and CP content but low fibre content (Kemp *et al.*, 2010b). Red clover has CP levels of 22-30%, NDF levels of 34-41%, ADF levels of 25-38% and a ME ranging from 9 to 13 MJ per kg DM (Table 1-1). Red clover contains phyto-oestrogens and formononetin that can affect sheep reproductive performance but does not affect lamb growth (Charlton and Stewart, 1999, de Ruiter *et al.*, 2007). Lambs grazing red clover were reported to have liveweight gains of 215 to 305 g per day (Fraser *et al.*, 2004, Moorby *et al.*, 2004).

1.4.6 Alternative forages used as herb-clover mix

There has been growing interest in the use of herb-clover mixed swards containing plantain, chicory, red clover and white clover for sheep production (Cranston *et al.*, 2015). Each of the species in the herb-clover mix, when offered as a monoculture, can provide an alternative to traditional ryegrass pastures. Individually, they are known to improve animal growth performance compared with ryegrass pastures (Fraser *et al.*, 2004, Moorehead *et al.*, 2002, Scales *et al.*, 1995). As monocultures, the usefulness of these species are limited due to the seasonality of their production (Cranston *et al.*, 2015)**.** These species in a mixed sward, therefore, can provide a more reliable source of feed throughout a greater period of the year due to differences in their optimal growing seasons.

Many studies have shown that herb-clover mix can increase lamb liveweight gains (Golding *et al.*, 2011, Corner-Thomas *et al.*, 2014, Somasiri *et al.*, 2015, Somasiri *et al.*, 2016a) due to the herb-clover mix having a higher digestibility and nutritive value than ryegrass pastures (Kenyon *et al.*, 2010, Golding *et al.*, 2011, Sinhadipathige *et al.*, 2012, Cranston *et al.*, 2015, Somasiri *et al.*, 2015, Somasiri *et al.*, 2016c). Weaned lambs grazing herb-clover mix during spring and autumn were found to have liveweight gains of 200 to 360 g per day whereas lambs on perennial ryegrass white clover mixes had gains of 56 to 320 g per day (Golding *et al.*, 2011, Cranston *et al.*, 2015, Somasiri *et al.*, 2015, Somasiri, 2014, Somasiri *et al.*, 2016a).

Lambs grazing the mix-herb forages had greater live weight gains and therefore achieved slaughter weights earlier than those on traditional perennial ryegrass white clover pastures (Ekanayake *et al.*, 2017, Corner-Thomas *et al.*, 2018b, Ekanayake *et al.*, 2018). Somasiri *et al.* (2016b) and Kenyon *et al.* (2017) reported that lambs grazing herb-clover mixes had a heavier carcass weight, increased DO% and increased GR compared to lambs on traditional perennial ryegrass pastures. The greater digestibility and nutritive value of herb-clover mixes may be useful to support the early weaning of lambs as a means of providing a nutrition replacement to milk (Corner-Thomas *et al.*, 2018a).

1.5 Effects of finishing lambs on different forages on carcass and meat quality characteristics

Diet type can influence animal age at slaughter and the composition of muscles (Purchas *et al.*, 1989). Direct effects of forage on meat quality characteristics are usually minimal but effects are exerted through animal age or weight at slaughter (Purchas *et al.*, 1989). Lambs offered forages with higher quality and digestibility, i.e. chicory, chicory and arrowleaf clover (*Tridolium vesiculosum)*, white clover and lucerne (*Medicago* sativa) produced heavier and fatter carcasses than those offered ryegrass (Table 1-2).

Table 1-2 Carcass characteristics: carcass weight, dressing out percentage, muscle-to-bone ratio and GR of lambs finished with different forage treatments.

Reference (Origin)	Treatment	Carcass weight (kg)	Dressing out %	Muscle : Bone	GR
Fraser *et al.* (1996) (NZ)	Chicory	18.3	47.9	3.49	9.8
	Plantain	16.8	47.9	3.47	8.4
	White Clover	20.1	48.3	3.51	10.8
	Ryegrass	15.6	45.2	3.43	7.2
(De Brito *et al.*, 2016) (AUS)	Bladder clover	21.7	49.2[a]	-	9.0[a]
	Brassica	23.5	51.5[a]	-	12.7[b]
	Chicory + Arrowleaf clover	25.1	54.7[b]	-	13.6[b]
	Lucerne + Phalaris	22.1	51.3[a]	-	9.9[a]
	Lucerne	24.9	54.7[b]	-	13.5[b]

[ab] Values within a study with different superscript are different from each other ($P<0.05$)

Studies investigating forage diets on lamb performance have extended their research to look at the forage effects on meat quality characteristics (Fraser *et al.*, 1996, Campbell *et al.*, 2011, Schreurs *et al.*, 2013). The meat quality characteristics that will be discussed in this section are pH, colour, tenderness and water-holding capacity.

1.5.1 Ultimate pH

Generally, forage diets for lambs do not alter meat pH (Table 1-3) (Hopkins *et al.*, 1995b, Schreurs *et al.*, 2013). Campbell *et al.* (2011), however, found that lambs that grazed on Radish (*Raphanus sativa*) had higher pH compared to other treatments

(Table 1-3) and speculated that it may have been a result of lambs on Radish only maintaining their weight and that some lost weight which is likely to have depleted glycogen stores. On the contrary, Hopkins *et al.* (1995a) reported a lower meat pH when lambs were fed forage rape (*Brassica* napus) compared to irrigated pasture. The lower pH in forage rape fed lambs was explained by increased weight gain (>200g/day) throughout the experiment indicating more glycogen reserves and no nutritional stress. The difference in findings may be due to a seasonality difference in crop production and nutritional value. The difference in pH, however, was negligible as they were within the acceptable pH threshold of below 5.8-6.0.

Table 1-3 Meat ultimate pH from lambs finished with different forage treatments.

Reference	Origin	Treatment	Ultimate pH
Campbell *et al.* (2011)	NZ	Brassica (Goliath)	5.58[a]
		Brassica (Winfred)	5.59[ab]
		Turnip	5.64[b]
		Radish	5.64[b]
		Pasture	5.62[ab]
		Plantain	5.51[ab]
		Red Clover	5.58[a]
Schreurs *et al.* (2013)	NZ	Perennial ryegrass pasture	5.83
		Chicory herbage mix	5.84
		Plantain herbage mix	5.82
Hopkins *et al.* (1995a)	AUS	Forage rape	5.49[a]
		Irrigated pasture	5.58[b]
Hopkins *et al.* (1995b)	AUS	Chicory	5.56
		Lucerne	5.56

[ab] Values within a study with different superscript are different from each other. ($P<0.05$)

1.5.2 Meat colour

In general, no differences in the colour of meat have been identified in lambs fed different forages (Table 1-4). Although Elmes (2013) objectively measured redder and darker meat when lambs grazed lucerne or ryegrass, the difference in chroma meter values were not large enough for a visually observable colour difference.

Kim *et al.* (2012) and Campbell *et al.* (2011) carried out a colour stability experiment on meat from lambs offered different forage treatments and found that meat from lambs fed ryegrass and plantain had superior colour stability whereas lambs fed red clover had poor colour stability. They also found that lucerne and chicory fed lambs had the most discolouration when examining at hue angle values and discolouration scores over 7 days (Kim *et al.*, 2012). Lambs fed on forage legumes have a higher proportion of unsaturated to saturated fatty acids (Fraser *et al.*, 2004) which can contribute to oxidative instability, inducing oxymyoglobin to form metmyoglobin causing undesirable brown colour (Kim *et al.*, 2012).

Table 1-4. Objective measures of meat colour from lambs finished with different forage treatments.

Reference (Origin)	Treatment	Colour L* (Lightness)	Colour a* (Redness)	Colour b* (Yellowness)	Hue Angle
Kim *et al.* (2012) (NZ)	Ryegrass	-	25.7[b]	-	24.5
	Lucerne	-	24.8[a]	-	25.1
	Chicory	-	25.4[a]	-	24.9
	Plantain	-	25.5[b]	-	25.1
	Red clover	-	27.0[c]	-	25.4
Campbell *et al.* (2011) (NZ)	Brassica (Goliath)	41.0	20.3	-	-
	Brassica (Winfred)	41.0	20.2	-	-
	Turnip	40.8	20.5	-	-
	Radish	41.5	20.7	-	-
	Pasture	41.4	20.2	-	-
	Plantain	41.6	21.3	-	-
	Red Clover	40.8	20.5	-	-
Schreurs *et al.* (2013) (NZ)	Perennial ryegrass pasture	40.9	14.8	-	-
	Chicory herbage mix	40.9	14.7	-	-
	Plantain herbage mix	41.6	15.3	-	-
Elmes (2013) (NZ)	Lucerne	40.93[c]	15.14[ab]	11.46[b]	-
	Ryegrass	41.42[b]	15.25[a]	11.70[ab]	-
	Titan	42.02[a]	14.69[b]	11.78[a]	-
Hopkins *et al.* (1995b) (AUS)	Chicory	36.2	14.2	7.0	-
	Lucerne	36.8	14.1	6.9	-
De Brito *et al.* (2016) (AUS)	Bladder Clover	38.0	15.5	1.2	-
	Hybrid Forage Brassica	37.2	16.0	1.1	-
	Lucerne	38.5	15.2	1.2	-
	Chicory + Arrowleaf clover	38.9	15.8	1.5	-
	Lucerne + Phalaris	38.0	15.9	1.6	-

[abc] Values within a study with different superscript are different from each other. (P<0.05)

1.5.3 Tenderness

Forage effects on meat tenderness are usually minimal and usually exerted through animal age or weight at slaughter (Purchas *et al.*, 1989). Table 1-5 illustrates shear force measures of meat from lambs under different forage treatments. Consumers found no differences in tenderness of meat of lambs from different forage treatments although there was a difference in shear force values when measured objectively (Campbell *et al.*, 2011, Elmes, 2013; Table 1-5). A study conducted by Schreurs *et al.* (2013), showed that lambs fed a plantain mix had significantly lower shear force values compared to lambs fed ryegrass and chicory although sensory testing was not done (Table 1-5). Elmes (2013) found that meat from lambs finished on a ryegrass diet had higher shear force values compared to lucerne and titan. The difference in shear force, however, was not large enough to be observable by consumers. Campbell *et al.* (2011) found that there were no significant differences in shear force values of lambs fed any of the different forages.

In a sensory study conducted by Young *et al.* (1994), it was found that lambs fed phalaris (*Phalaris aquatics*) had more tender meat. The effects of increased in tenderness of lambs on phalaris, however, was negated by the increase in foreign flavours on the overall acceptability. Other drivers that could contribute to the differences in shear force values are the intramuscular fat percentage, collagen concentration and solubility and age of the animal at slaughter (Young *et al.*, 1994).

Table 1-5. Objective measurements of meat tenderness from lambs finished with different forage treatments.

Reference	Origin	Treatment	Shear Force (kgF)
Campbell *et al.* (2011)	NZ	Brassica (Goliath)	7.9
		Brassica (Winfred)	7.7
		Turnip	6.7
		Radish	7.3
		Pasture (Ryegrass)	5.8
		Plantain	7.4
		Red Clover	6.8
Elmes (2013)	NZ	Lucerne	5.01[b]
		Ryegrass	5.75[c]
		Titan	4.57[a]
Schreurs *et al.* (2013)	NZ	Perennial ryegrass pasture	3.73[b]
		Chicory herbage mix	3.18[b]
		Plantain herbage mix	2.98[a]
Hopkins *et al.* (1995b)	AUS	Chicory	4.4
		Lucerne	4.2

[abc] Value with different superscript are different from each other. (P<0.05)

1.5.4 Water-holding capacity

Generally, forage diets for lambs do not alter the meat water-holding capacity. De Brito *et al.* (2015) found an increase in purge loss when lambs were fed on bladder clover (*Tridolium spumosum)* and lucerne (*Medicago sativa*)-phalaris (*Phalaris aquatica*) forage compared to rape kale cross (*Brassica napus*), lucerne and chicory-arrowleaf clover (*Trifolium vesicuolsum*) forage. In 2016, however, De Brito *et al.* (2016) found no differences in purge losses among the same forage treatments. Other studies have not found differences in purge loss and cooking loss of lambs fed different forages (Table 1-6).

No differences in meat juiciness have been found when finishing lambs with different forage treatments via sensory panel (Fraser *et al.*, 2004, Campbell *et al.*, 2011). This finding is likely due to juiciness being affected by multiple factors that influence the amount of water held in meat and the quantity of intramuscular fat present and succulence in sensory analysis (Purchas *et al.*, 1989). It is not expected that forages would alter water-holding capacity unless they influence meat composition (Pethick *et al.*, 2005a).

Table 1-6 Objective measures of meat moisture content from lambs finished with different forage treatments.

Reference	Origin	Treatment	Purge Loss (%)	Cooking Loss (%)
De Brito *et al.* (2015)	AUS	Bladder Clover	8.0[b]	20.6
		Rape Kale Cross	5.8[a]	20.4
		Chicory + Arrowleaf clover	6.7[ab]	21.1
		Lucerne + Phalaris	8.1[b]	21.5
		Lucerne	5.8[a]	21.2
De Brito *et al.* (2016)	AUS	Bladder Clover	8.1	20.5
		Brassica	6.0	20.4
		Chicory + Arrowleaf clover	6.7	20.0
		Lucerne + Phalaris	8.2	21.4
		Lucerne	5.9	21.2
Farouk *et al.* (2007)	NZ	Lotus pedunculatus	10.4	33.4
		Perennial Ryegrass	9.5	31.9
		White clover	9.6	30.8

[ab] Values within a study with different superscript are different from each other. (P<0.05)

1.6 Effects of early weaning on the growth of lambs

Although there are a number of positive outcomes associated with early weaning of lambs for farm management, early weaning is a stressful event for lambs that can negatively impact growth rates by causing a reduction in feed intake (Lee *et al.*, 1990). Rattray *et al.* (1976) found that early weaning lambs at three to five weeks of age had reduced survival and live weight gain when compared to lambs weaned at 12-weeks of age. Studies with lambs weaned between four to six weeks of age onto traditional ryegrass pastures reported poor growth rates(<190g/day;(Geenty, 1979, Geenty and Sykes, 1981). Lambs born to mature ewes, however, have been weaned at eight weeks of age with no detrimental effects on their growth (Rattray *et al.*, 1976) and lambs born to hoggets can be weaned onto traditional perennial ryegrass white clover pasture at an average of 10 weeks of age with no detrimental effect on lamb growth (Mulvaney *et al.*, 2009).

Although early weaning can negatively affect lamb growth, weaning onto alternative forages such as lucerne, white clover and prairie grass can increase lamb growth rates compared to weaning onto ryegrass pastures (Cruickshank *et al.*, 1985). This suggests that early weaning will not impede growth when forage with a greater nutritive value is provided after weaning (Cruickshank *et al.*, 1985, Jagusch *et al.*, 1971). Weaning lambs at 12 weeks of age onto high quality pastures such as herb-clover mix chicory, plantain, white clover and red clover can increase growth compared to traditional ryegrass pasture (Cranston *et al.*, 2016, Kenyon *et al.*, 2017). Further, lambs weaned as early as 8-weeks of age onto herb-clover mix were able to achieve growth rates that matched lambs weaned at 12-13 weeks onto unrestricted ryegrass pasture intake (Ekanayake *et al.*, 2018).

In a study by Galvani *et al.* (2014), it was found that milk intake was the main factor affecting the growth performance of early-weaned lambs as the nutrition from milk allowed for better lamb development. The authors suggested a lambs' dependence on milk was due to the rumen not being fully developed and being ineffective in digesting solid food. It has been reported, however, that using herb-clover mix increases growth of lambs to weaning (Corner-Thomas *et al.*, 2014). Therefore, using herb-clover mix pre-weaning can be a useful farm management tool to allow for increased pre-weaning average daily gain (ADG) to obtain greater post-weaning growth.

1.7 Effects of early weaning of lambs on carcass characteristics and meat quality characteristics

Most studies encompassing early weaning of lambs have focused on the effects of early weaning on growth rates for carcass weight (Morris and Kenyon, 2014, Danso *et al.*, 2018). This is because sheep farmers in New Zealand are paid a premium for the production of lean lamb carcasses that have a weight between 17 to 21 kg (New Zealand Meat Classification Authority, 2004) (Schreurs, 2012). Weaning stresses can cause a drop in food consumption and decrease growth rate and may modify body composition through the mobilisation of tissue (Caneque *et al.*, 2001, Lee *et al.*, 1990).

Consumer perceived meat qualities and likely eating experience determine the willingness of consumers to purchase a meat product (Troy and Kerry, 2010). Studies on the effects of early weaning on meat quality characteristics have been carried out in Spain, where it was found that early weaned lambs produced leaner carcasses with lower collagen values (Caneque *et al.*, 2001). The effects of early weaning on carcass characteristics and meat quality in New Zealand pastoral rearing conditions, however, has not been investigated.

1.8 Research Objectives

From previous research, it can be seen that there is potential to manipulate feeding forages and weaning practices of lambs to alter their growth and carcass weight. Few studies, however, have taken a "pasture-to-plate" approach to consider the effects of forage feed and weaning practices on carcass composition and meat quality. The information obtained from this research is intended to allow for better understanding on how changes in weaning practices and forage diet are reflected in the final product in terms of carcass and meat quality.

We hypothesise that early weaning of lambs onto herb-clover mix can produce lambs equal, in terms of carcass and meat quality characteristics, to lambs not weaned early on traditional ryegrass pasture. The objectives of this research are as follow:

1. To investigate effects of weaning lambs at 8 compared to 15 weeks of age on carcass and meat quality characteristics.
2. To compare the differences in carcass and meat quality characteristics of lambs finished on herb-clover mix compared to perennial ryegrass-based pasture.

Chapter 2: Experimental Design and Methods

In order to test the hypotheses, a study was conducted to assess the impact of weaning practices and forage on the carcass and meat quality of Romney lambs.

2.1 On-farm management

Seventy-five mixed age (3-5 years) Romney ewes, rearing twin lambs (n=150) were managed at Massey University's Keeble farm, 7 km southeast of Palmerston North, New Zealand. Lambs were weighed, tagged and matched to their dam within 12 hours of birth. Lambs were drenched at docking and then every 28 days using Ancare 'Matrix' triple combination drench (Merial Ancare, Manukau City, New Zealand). All the ewes and lambs were maintained on permanent ryegrass-white clover (RG-WC) pasture prior to treatment allocation.

On the 21 October 2016 (56 days after mid-point of lambing), ewes that had both twin lambs weighing at least 16 kg were allocated to one of three treatments:

(i) Lambs with dams on RG-WC pasture (GRASS) (lambs n=50)

(ii) Lambs with dams on a herb-clover mix (plantain, chicory, red clover and white clover) (HERB) (lambs n=50)

(iii) Lambs weaned early at 8 weeks-of-age, onto a herb-clover mix pasture and dams moved to RG-WC pasture (EARLY) (lambs n=50)

The RG-WC pasture used in this study had not been sown within the last 5 years and contained ryegrass (19.2%), other grasses (64.5%), white clover (1.7%) and weeds (1.5%). The herb-clover mix contained chicory (54.8%), plantain (19.4%), red clover (6.3%), white clover (4.2%), and weeds (1.3%). Ewes and lambs in the HERB treatment and the lambs in the EARLY treatment underwent a 4-day adjustment period to the herb-clover mix prior to the start of the experiment where they grazed the herb-clover mix for increasing intervals (2, 4, 8 and 24-hours) over 4 days.

Throughout the study, ewes and lambs were offered their allocated diets *ad libitum* by rotational grazing. The *ad libitum* feeding conditions were ensured by maintaining RG-WC pasture covers greater than 1200 kg DM/ha (Morris and Kenyon,

2004) and herb mixes with sward heights of 7 - 20 cm (Somasiri *et al.*, 2016c, Kenyon and Webby, 2007). Lambs were weighed on 21st October 2016 (start), 12th December 2016 (first slaughter) and 24th January 2017 (second slaughter). At 15 weeks of age (12th December 2016), lambs from GRASS and HERB treatments were weaned. Lambs from all three treatments with a live weight of >35 kg were sent for slaughter (n=28). Four lambs in the EARLY treatment achieved the target slaughter weight at 15 weeks, whereas 15 lambs in the HERB and nine lambs in the GRASS treatment achieved this weight (Chapter 3; Table 3-1). The lambs that weighed <35kg were grazed together on RG-WC pasture for an additional 6 weeks. After this period, lambs with a live weight of >35 kg were sent for slaughter (25th January 2017; n=93).

2.2 Abattoir management

Lambs were slaughtered at a commercial abattoir (Alliance Group Ltd, Dannevirke). Carcasses were prepared following standard commercial dressing procedures. Each carcass was given an identification number that was linked to the electronic ID of each sheep allowing tracing of information from individual sheep. Hot-carcass weight was measured at the processing plant. Lean meat yield (LMY) and the GR soft tissue depth (tissue depth 110 mm from the midline on the 12th rib) was obtained using the Alliance Group VIAscan® system. The carcasses were chilled at 4°C for 24 hours and then the left leg (bone-in, short-leg) was collected from each carcass, vacuum-packed with their respective carcass identification tag and frozen at -20°C. Six leg samples were missed during sampling at the processing plant and two lambs did not have VIAscan information leaving 115 leg samples for dissection and 119 carcasses with VIAscan information.

The ADG of lambs that achieved the target slaughter weight for the first slaughter was calculated using weight of lambs at 8 and 15 weeks of age (52 days; ADG_{8-15w}). The average daily gain of lambs in the second slaughter was calculated using weight of lambs at 8 and 21 weeks of age (96 days; ADG_{8-21w}).

2.3 Dissection of lamb leg and Carcass Characteristic Analysis

Leg samples (n=115) were analysed over a 6-week period with treatments balanced across each day of analysis. The samples were thawed at 1°C for 24 hours prior to dissection. The leg in packaging was weighed and the leg was then removed from the packaging and both the leg and packaging dried with paper towels and weighed. Eight muscles (gracilis, sartorius, pectineus, semimembranosus, adductor, biceps femoris, semitendinosus and quadriceps femoris) were dissected from each leg and weighed individually. The semimembranosus was vacuum packed and frozen for meat quality analyses. The total dissectible fat was also obtained from the leg and weighed.

The femur was removed from the leg and was weighed and measured length-wise. The muscle-to-bone ratio (M:B; Equation 4) (Johnson *et al.*, 2005b) and muscularity (Equation 5) were calculated (Purchas *et al.*, 1991a). Muscularity was expressed as the ratio of muscle depth to the length of the femur. Lean meat yield was calculated as a percentage of all dissected muscles to the leg weight. Dissectible fat and bone weight were expressed as weights and percentages of the total leg weight.

Equation 4:

$$M{:}B = muscle\ weight\ (semimembranosus + adductor + biceps\ femoris + semitendinosus + quadriceps\ femoris)/bone\ weight$$

Equation 5:

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

2.4 Meat Quality Tests and Calculations

The objective meat quality tests for pH, colour, water holding capacity, sarcomere length and shear force were carried out at Massey University, Palmerston North. The procedure used is outlined in Figure 2-1 which also indicates how the muscle was sub-portioned for all the tests and measures.

2.4.1 Ultimate pH

Ultimate pH was measured at three locations, across a transverse internal cut of the semimembranosus with a pH spear (Portion 1; Eutech Instruments, Singapore). The pH spear was calibrated to pH 4.01, 7.00 and 10.01 standard buffers. The three measurements were averaged to obtain a single pH value for each sample.

2.4.2 Colour

Meat colour was measured on the internal cut surface of the muscle after 30 minutes of exposure to air (Portion 1). The colour was measured using a Minolta Colour Meter calibrated to a standard white tile supplied by the manufacturer (CR-200, Konica Minolta Photo Imaging Inc. Mahwah, NJ, USA). The CIE L*(lightness), a*(redness) and b* (yellowness) readings were obtained at three locations across the meat sample. The three readings were averaged to obtain the average L*, a* and b* values for each sample.

Hue angle (Equation 6) and chroma (Equation 7) were calculated from the L*, a* and b* values using the equations below:

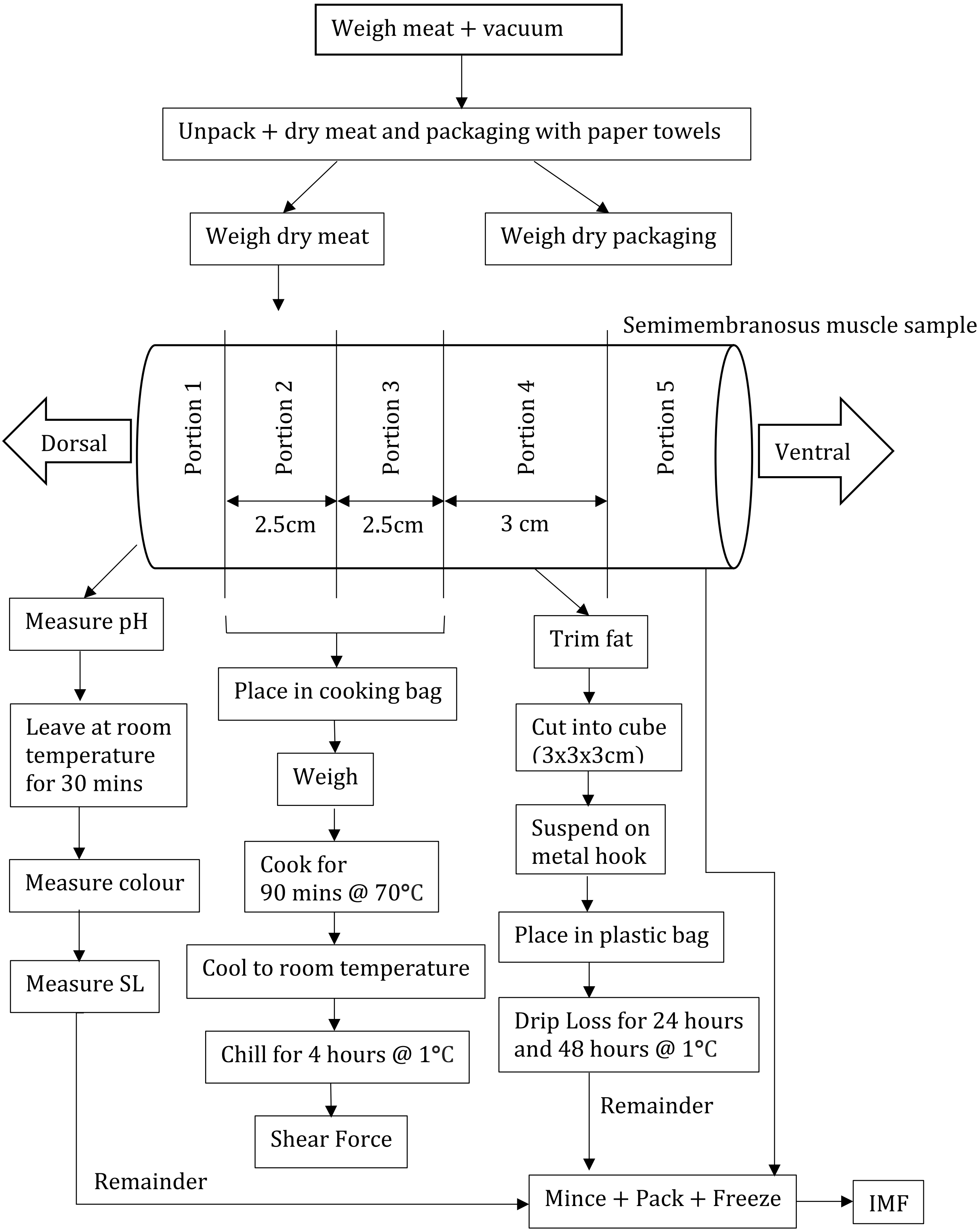
Equation 6:

$$\text{Hue Angle} = \arctan\left(\frac{b*}{a*}\right) \times 57.296$$

Equation 7:

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

Figure 2-1 A schematic diagram of the partitioning of the lamb Semimembranosus muscle for meat quality analysis. SL = Sarcomere length, IMF = Intramuscular fat.



2.4.3 Water holding capacity (WHC)

Water holding capacity was assessed as thaw loss, drip loss of the raw meat sample and cooking loss. Thaw loss (Equation 8) was measured using the weight of the thawed whole leg in a vacuum pack, weight of the paper dried leg and weight of the paper dried vacuum packaging (Figure 2-1).

Equation 8:

$$\text{Thaw loss (\%)} = \frac{[(\text{Whole weight} - \text{packaging weight}) - (\text{Whole leg weight})]}{(\text{Whole weight} - \text{packaging weight})} \times 100$$

Drip loss (Equation 9a and 9b) was measured by suspending a cube of raw meat from portion 4 (Figure 2-1) (3x3x3cm) on a metal hook in a plastic bag and chilled at 1°C. The raw meat cube was patted dry with paper towels and weighed again after 24 and 48 hours respectively.

Equation 9a:

$$\text{Driploss}_{24\text{hr}}\ (\%) = \frac{\text{weight}_{0\text{hr}} - \text{weight}_{24\text{hr}}}{\text{weight}_{0\text{hr}}} \times 100$$

Equation 9b:

$$\text{Driploss}_{48\text{hr}}\ (\%) = \frac{\text{weight}_{0\text{hr}} - \text{weight}_{48\text{hr}}}{\text{weight}_{0\text{hr}}} \times 100$$

Cooking loss (Equation 10) was measured by cutting two 2.5cm-thick slices (Portion 2 and 3; Figure 2-1) of semimembranosus, weighing and placing them in a plastic bag (Figure 2-1). The steaks were then cooked in a water bath (Contherm®, Model 370HL, Australia) at 70°C for 90 minutes, cooled to room temperature, and then chilled at 1°C for 4 hours, dried with paper towels and reweighed. Cooking loss was measured by the difference in total weight of the steaks before and after cooking and expressed as a percentage of the weight before cooking.

Equation 10:

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

2.4.4 Sarcomere length

Sarcomere length was measured by laser diffraction as described by Bouton *et al.* (1973). A small section of muscle from Portion 1 (Figure 2-1) approximately 8-10 mm long running along the direction of the fibres and 1mm thick was excised using a scalpel blade. The muscle strand was transferred onto a microscope slide, teased out using the ends of the scalpel blade. Once prepared, 1-2 drops of distilled water were added, and the muscle compressed between two microscope slides. The compressed muscle strand was passed through a helium-neon laser (632.8 nm, Melles Griot, Carlsbad, CA, USA) to create a diffraction pattern on a screen set 10cm from the sample. Ten repetitions of the distance between the diffraction bands were measured using a ruler and recorded in millimetres. Sarcomere length was calculated using Equation 11, where x=average of the 10 replicate measurements.

Equation 11:

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

Where; x = Average distance (mm) between first order diffraction bands.

2.4.5 Shear Force

Shear force was measured as the force required to shear through a 13mm diameter core from the cooked muscle sample. After the two pieces of 2.5 cm steak (Portion 2 and 3) were cooked, they were cooled to room temperature and chilled for 4 hours (Figure 2-1). Six 13 mm diameter cylindrical cores were prepared from the cooked and chilled portions using a stainless steel corer.

The cores were sheared perpendicular to the direction of muscle fibres with a standard V-shaped blade using a texture analyser (TMS-Pilot Texture analyser, USA) connected to a tablet running TL-Touch software (version 1.18-408). The cutting speed was set to 20 cm/min and six measurements of peak area (total work done) and peak load (peak force) were obtained for each sample. The average of the six repetitions were designated as the shear force measurement for each sample.

2.4.6 Intramuscular fat (IMF)

The remainder muscle from sarcomere length (Portion 1; Figure 2-1), drip loss measurements (Portion 4; Figure 2-1) and Portion 5 (Figure 2-1) were finely minced (Kenwood MG450, 3mm hole-plate), packed in a small zip-lock bag and frozen for IMF measurements. Ten samples (from five ram and five ewe lambs) were randomly selected from each treatment and analysed for fat content using solvent extraction with the Soxtec System (AOAC 991.36).

2.5 Statistical Analysis

The hot-carcass weight, total yield, GR soft tissue depth, leg yield, carcass characteristics and meat quality characteristics were presented as the mean and standard error of the mean. The data was analysed using a mixed linear model (PROC MIXED, SAS) with forage-weaning treatment as the fixed effect. Hot-carcass weight was used as a covariate to analyse GR soft tissue depth, leg weight, the eight muscles dissected from the leg, bone weight, fat weight, muscle-to-bone ratio and muscularity. pH was used as a covariate to analyse L*, a*, b*, hue angle, chroma, $driploss_{24hr}$, $driploss_{48hr}$, cooking loss percentage and peak load. The hot-carcass weight and pH covariates were removed from the statistical model if not significant ($P>0.05$).

Chapter 3: Results

3.1 Carcass Characteristics – On-farm, abattoir and laboratory measurements

Percentage of lambs that reached slaughter weight

The percentage of lambs in each treatment group that achieved the target slaughter weight of 35 kg at the first slaughter date (12 December 2016; 15 weeks old) was 30% in the HERB, 10% in the GRASS and 8% for lambs in the EARLY treatment. The percentage of lambs in each treatment group that did not reach the target slaughter weight of 35 kg by the second slaughter (25 January; 21 weeks old) was 30% in the GRASS treatment, 20% in the EARLY and 8% in the HERB treatment.

Growth and carcass characteristics

Between week 8 and 15, while lambs were on their treatments, lambs in the HERB treatment grew faster than lambs in the GRASS and EARLY treatments ($P<0.05$; Table 3-1). The ADG_{8-21w} of lambs in the HERB treatment was greater than both the EARLY treatment and GRASS treatment ($P<0.05$), which did not differ ($P>0.05$). At the first slaughter, lambs in the EARLY treatment had a lower slaughter weight than lambs in the GRASS and HERB treatments ($P<0.05$). At the second slaughter, however, lambs in the GRASS treatment had a lower slaughter weight ($P<0.05$) compared to the lambs in EARLY and HERB treatments ($P>0.05$).

Lambs in the HERB treatment had a heavier carcass than lambs in the GRASS treatment ($P<0.05$; Table 3-1), lambs in the EARLY treatment were intermediate and did not differ from either the HERB and GRASS treatments ($P>0.05$). Lambs across all three treatments had a similar dressing out percentage, VIAscan® lean meat yield, leg yield, loin yield and shoulder yield ($P>0.05$). The VIAscan® GR soft tissue depth was greater for lambs in the HERB treatment than both the EARLY and GRASS treatments ($P<0.05$).

Table 3-1 Average daily gain (ADG (g/day); between weeks 8 and15 and week 8 and 21), on-farm and abattoir measured carcass characteristics (mean ± standard error of mean) of lambs in three treatments: (i) lambs weaned early at 8 weeks onto herb-clover mix (EARLY); (ii) lambs with dam on ryegrass-white clover pasture and weaned at 15 weeks (GRASS); (iii) lambs with dam on herb-clover mix and weaned at 15 weeks (HERB).

	n	Early	Grass	Herb	Hot-carcass Weight Covariate[3]
On-farm measurements					
$ADG_{8\text{-}15weeks}$ (g/day) [1]	150	205.8 ± 7.2^a	246.1 ± 7.2^b	277.1 ± 7.2^c	-
$ADG_{8\text{-}21weeks}$ (g/day) [1]	121	255.8 ± 8.0^a	267.8 ± 8.5^a	307.0 ± 7.4^b	-
Number of lambs	28	4	9	15	-
Slaughter weight $_{slaughter\text{-}1}$ (kg)	28	38.9 ± 0.66^b	36.9 ± 0.44^a	36.4 ± 0.34^a	-
Number of lambs	121	38	33	44	-
Slaughter weight $_{slaughter\text{-}2}$ (kg)	121	40.1 ± 0.47^b	38.6 ± 0.50^a	40.0 ± 0.44^b	-
Proportion achieving slaughter weight (%)	-	76	66	88	-
Abattoir measurements-VIAscan®					
Dressing Out (%)	121	42.7 ± 0.33	43.2 ± 0.35	43.4 ± 0.30	-
Hot-carcass weight (kg)	121	17.1 ± 0.25^{ab}	16.7 ± 0.26^a	17.4 ± 0.23^b	-
Lean meat yield (%)	119	54.5 ± 0.38	54.3 ± 0.41	54.2 ± 0.36	-
GR soft tissue depth (mm) [2]	119	6.8 ± 0.44^a	6.5 ± 0.47^a	8.2 ± 0.41^b	NS
Leg Yield (%)	119	22.3 ± 0.22	22.0 ± 0.23	22.1 ± 0.20	-
Loin Yield (%)	119	14.8 ± 0.12	14.7 ± 0.13	14.9 ± 0.12	-
Shoulder Yield (%)	119	17.3 ± 0.15	17.7 ± 0.15	17.3 ± 0.14	-

[abc] Values within rows with different superscripts are significantly different ($P<0.05$).
[1] ADG = Average daily gain.
[2] GR soft tissue depth = measurement of total tissue depth (mm) over the 12th rib at a point 11cm from the midline of the carcass. Hot-carcass weight was used as a covariate but was removed from the statistical model when found to be not significant ($P>0.05$).
[3] Dash indicates carcass weight not considered as covariate; NS: covariate not significant and removed from the statistical model.

Physical dissection of lamb leg

The weight of the whole short-leg from lambs in GRASS treatment was lighter than both HERB and EARLY treatments ($P<0.05$; Table 3-2). Lambs in the GRASS treatment had a lighter semimembranosus compared to lambs in the EARLY and HERB treatments ($P<0.05$). Lamb biceps femoris weight was greater in the HERB treatment than the GRASS treatment ($P<0.05$) and the EARLY treatment was intermediate but did not differ from HERB and GRASS treatments ($P>0.05$). There was also no difference in individual muscle weights of the gracilis, sartorius, pectineus, adductor, semitendinosus and quadriceps femoris ($P>0.05$).

Lambs in the EARLY treatment had a heavier femur bone compared to lambs from the GRASS treatment ($P<0.05$; Table 3-3) with HERB treatment being intermediate and did not differ from the other treatments ($P>0.05$). Dissectible fat weight was greater for lambs from the HERB treatment than GRASS treatment ($P<0.05$) with lambs in the EARLY treatment being intermediate ($P>0.05$). Although muscle and fat weights differed between treatments, the proportion of bone and fat did not ($P>0.05$).

Lambs in the HERB treatment had a greater muscle-to-bone ratio (M:B) than lambs in the EARLY treatment ($P<0.05$; Table 3-3) with those in GRASS treatment intermediate ($P>0.05$). The muscularity index was greater in lambs of the HERB treatment compared to both the EARLY and GRASS treatments ($P<0.05$). The calculated lean meat yield and intramuscular fat percentage was similar across the three treatments ($P>0.05$).

Table 3-2 Left leg (bone-in, short-leg) and individual muscle weights (g; mean ± standard error of mean; n=119) of lambs in the three treatments: (i) lambs weaned early at 8 weeks onto herb-clover mix (EARLY; n=38); (ii) lambs with dam on ryegrass-white clover pasture and weaned at 15 weeks (GRASS; n=33); (iii) lambs with dam on herb-clover mix and weaned at 15 weeks (HERB; n=44). Hot-carcass weight was included as a covariate in the statistical model but was removed if found to be non-significant (P>0.05).

Leg and Muscles	Treatment (n)			Hot-carcass Weight Covariate
	Early (38)	Grass (33)	Herb (44)	
Leg (g)	2399.8 ± 33.5[b]	2301.9 ± 35.9[a]	2416.5 ± 31.1[b]	NS
Gracilis (g)	47.9 ± 0.91	48.2 ± 0.97	48.5 ± 0.84	NS
Sartorius (g)	10.7 ± 0.30	10.8 ± 0.32	11.0 ± 0.28	NS
Pectineus (g)	30.4 ± 0.68	30.1 ± 0.73	30.9 ± 0.63	NS
Semimembranosus (g)	261.9 ± 4.43[b]	248.1 ± 4.75[a]	261.5 ± 4.11[b]	NS
Adductor (g)	108.8 ± 2.22	104.9 ± 2.38	109.8 ± 2.06	NS
Biceps femoris (g)	254.9 ± 4.76[ab]	248.3 ± 5.10[a]	262.5 ± 4.42[b]	NS
Semitendinosus (g)	96.7 ± 1.92	95.4 ± 2.06	98.4 ± 1.78	NS
Quadriceps (g)	375.7 ± 5.69	371.0 ± 6.10	381.5 ± 5.29	NS
Other muscles (g)	344.6 ± 6.32	341.4 ± 6.78	355.4 ± 5.87	-

[ab] Values within rows with different superscripts are significantly different (P<0.05).

Table 3-3 Carcass characteristics obtained by physical dissection (mean ± standard error of mean) for lambs in three treatments: (i) lambs weaned early at 8 weeks onto herb-clover mix (EARLY; n=38); (ii) lambs with dam on ryegrass-white clover pasture and weaned at 15 weeks (GRASS; n=33); (iii) lambs with dam on herb-clover mix and weaned at 15 weeks (HERB; n=44). Hot-carcass weight was used as a covariate in the statistical model analysis for bone weight, fat weight, muscle-to-bone ratio, muscularity and intramuscular fat (IMF) but was removed if found to be non-significant (P>0.05).

Carcass Characteristics	n	EARLY	GRASS	HERB	Hot-carcass Weight Covariate
Bone weight (g)	119	169.8 ± 2.36^{b}	160.5 ± 2.53^{a}	164.9 ± 2.19^{ab}	NS
Bone percent (%)	119	7.1 ± 0.10	7.0 ± 0.11	6.9 ± 0.10	-
Bone length (cm)	119	17.4 ± 0.09	17.4 ± 0.09	17.3 ± 0.08	-
Fat weight (g)	119	222.3 ± 8.71^{ab}	211.1 ± 9.35^{a}	240.4 ± 8.10^{b}	NS
Fat percent (%)	119	9.2 ± 0.30	9.2 ± 0.32	9.9 ± 0.28	-
Muscle-to-bone ratio	119	6.48 ± 0.10^{a}	6.69 ± 0.11^{ab}	6.79 ± 0.09^{b}	NS
Muscularity index[3]	119	0.45 ± 0.003^{a}	0.45 ± 0.004^{a}	0.46 ± 0.003^{b}	NS
LMY-calculated (%)[1]	119	78.6 ± 0.26	79.0 ± 0.28	78.4 ± 0.24	-
IMF (%)[2]	30	2.3 ± 0.20	2.3 ± 0.20	2.4 ± 0.20	NS

[ab] Values within rows with different superscripts are significantly different (P<0.05).
[1] LMY-calculated = lean meat yield calculated from muscle-to-bone ratio and percentage of dissected fat from whole left leg (bone-in, short-leg)
[2] IMF = Intramuscular fat; ten samples (consisting of five rams and five ewes) were randomly selected from each treatment for analysis
[3] Indicates the depth of muscle over each unit length of bone.

3.2 Meat Quality of Semimembranosus

The ultimate pH, L*, a* and b* values did not differ across the three treatments ($P>0.05$; Table 3-4). Ultimate pH, however, was a significant covariate when analysing b* values ($P=0.036$). Lambs in the EARLY treatment had greater hue angle compared to lambs in the HERB treatment ($P<0.05$) with lambs in the GRASS treatment being intermediate ($P>0.05$).

Thaw loss, drip loss at both 24 and 48 hours was not different among the three treatments ($P>0.05$; Table 3-4). The cooking loss was greater for lambs in the GRASS treatment compared to both the EARLY and HERB treatments ($P<0.05$). There was no difference in the total shear force work done, peak shear force and sarcomere length for lamb semimembranosus across the three treatments ($P>0.05$).

Table 3-4 Meat quality characteristics (mean ± standard error of mean; n=119) of lambs in three treatments: (i) lambs weaned early at 8 weeks onto herb-clover mix (EARLY); (ii) lambs with dam on ryegrass-white clover pasture and weaned at 15 weeks (GRASS); (iii) lambs with dam on herb-clover mix and weaned at 15 weeks (HERB). Ultimate pH was used as a covariate in the statistical model for L*, a*, b*, hue angle, chroma, $driploss_{24hr}$, $driploss_{48hr}$, cooking loss percentage and peak force but was removed if found to be non-significant (P>0.05).

Meat Quality Characteristics	Treatment (n)			Significance of Ultimate pH Covariate
	Early (38)	Grass (33)	Herb (44)	
Ultimate pH	5.52 ± 0.02	5.51 ± 0.02	5.51 ± 0.02	-
L*	38.3 ± 0.35	38.1 ± 0.38	38.7 ± 0.33	NS
a*	12.1 ± 0.15	12.2 ± 0.16	12.1 ± 0.14	NS
b*	3.10 ± 0.09	2.96 ± 0.09	2.90 ± 0.08	0.036
Hue Angle	14.3 ± 0.34^{b}	13.4 ± 0.37^{ab}	13.3 ± 0.32^{a}	NS
Chroma	12.5 ± 0.16	12.6 ± 0.17	12.5 ± 0.15	NS
Thaw Loss (%)	6.08 ± 0.26	6.38 ± 0.28	6.46 ± 0.54	-
$Driploss_{24hr}$ (%)	2.96 ± 0.19	2.93 ± 0.20	3.08 ± 0.17	NS
$Driploss_{48hr}$ (%)	3.97 ± 0.20	3.99 ± 0.21	4.13 ± 0.18	NS
Cooking Loss (%)	36.2 ± 0.39^{a}	38.0 ± 0.42^{b}	36.8 ± 0.36^{a}	NS
Total Work Done	20.3 ± 1.71	23.3 ± 1.84	22.6 ± 1.59	-
Peak Force	4.23 ± 0.15	4.52 ± 0.17	4.50 ± 0.14	NS
Sarcomere Length	1.70 ± 0.02	1.71 ± 0.02	1.69 ± 0.02	-

^{ab} Values within rows with different superscripts are significantly different (P<0.05)

Chapter 4: Discussion

The objective of this study was to investigate the effects of early weaning of lambs at 8 weeks of age onto herb-clover mix on carcass and meat quality characteristics in comparison to conventional weaning age at 15 weeks of age. Early weaning onto alternative forage crops such as the herb-clover mix is a potentially useful farm management tool when pasture availability is low to prevent feed competition between the ewe and her lambs and to provide focused nutrition to finish lambs.

4.1 Lamb growth

The growth rates of twin lambs on commercial farms has been reported to be 220g/day (Litherland and Lambert, 2000). Lambs in the current study achieved an ADG of at least 250g/day from weeks 8 to 21. The greater ADG of lambs in the HERB treatment indicated that the herb-clover mix has a higher feeding value than perennial ryegrass white clover pasture (Golding *et al.*, 2011, Cranston *et al.*, 2015, Kenyon *et al.*, 2017). The higher nutrient digestibility of herb-clover mix was likely to have led to a lower feed retention time and rumen gut fill leading to increased feed intake allowing greater liveweight gains (Somasiri *et al.*, 2016b, Litherland *et al.*, 2010). Although the herb-clover mix had a higher feeding value, early weaning of lambs onto herb-clover mix resulted in fewer lambs achieving the target slaughter weight at 15 and 21 weeks of age when compared to lambs grazing the herb-clover mix with their dams (HERB). This suggests that there was a growth impediment as a consequence of early weaning which may have been the result of a lack of milk (Galvani *et al.*, 2014), weaning behaviour (Campbell *et al.*, 2017) and grazing ability (Geenty and Sykes, 1981).

4.2 Carcass and Meat Quality Characteristics

Hot-carcass weight differences observed in the current study reflect differences in live weight with similar DO%. The lambs in HERB treatment had greater hot-carcass weights than those in GRASS. This finding is in agreement with Somasiri *et al.* (2016a) and Golding *et al.* (2011) who reported increased carcass weights when lambs were fed herb-clover mixes. Furthermore, greater carcass weights have been reported when weaned lambs were offered pure swards of plantain, chicory or white clover compared with ryegrass (Fraser and Rowarth, 1996). Although a positive relationship between live weight and DO% has been reported (Kirton *et al.*, 1984, Litherland *et al.*, 2010), no such relationship was identified in the current study. This was likely due the young age at which the lambs were slaughtered (Kirton *et al.*, 1984).

The lack of difference in LMY between treatments was not surprising given that the lambs were slaughtered at a set weight. Lambs in HERB treatment had the highest GR, which is likely to be due to these lambs having greater metabolisable energy (ME) intakes over the course of the study resulting in more nutrients and energy being available for the deposition of fat (Cranston *et al.*, 2015). This finding is supported by lambs in the HERB treatment having the greatest dissectible fat. The lambs in HERB treatment had the highest M:B and fat weight. This was also reported by Fraser and Rowarth (1996) who suggested that this increased muscle is associated with increased nutrient and energy intake.

The differences in semimembranosus and biceps femoris weights suggest that early weaning can promote larger muscle groups by increasing their growth rates in relation to the other muscles in the leg. Allometric growth rates of carcass and non-carcass components have been studied, however, studies regarding effects of early weaning and alternative forages on relative growth rates of individual leg muscles are lacking. Therefore, more research is needed in this area. With that said, the difference in individual muscles weight are likely to be of limited economic significance.

Differences were observed in bone weight but not length. This may be due to greater bone ossification, which is an indicator of a greater progression in maturity (Kirton *et al.*, 1975). Early weaning, and a change in diet which excludes milk at a younger age, may change the proportion and types of nutrients and metabolites available for bone growth, thus, it is possible that this signals for earlier bone ossification (Kirton *et al.*, 1975). It is also possible that the change of diet in conjunction with early weaning alters the nutrient metabolism and hormone signalling towards tissue deposition, increasing the degree of bone maturity (Lewis *et al.*, 2004). More research is needed to validate this finding and to understand if it has any commercial importance.

In general, early weaning and forage treatment had no effect on colour of the semimembranosus muscle. This is in agreement with studies which examined the effects of forage treatment on colour (Kim *et al.*, 2012, Campbell *et al.*, 2011, Hopkins *et al.*, 1995b). This finding was perhaps to be expected as differences in L* caused by diet are generally only observed between when feeding extremely different diets such as comparing pasture-fed and grain-fed lambs (Priolo *et al.*, 2001).

There was also no difference in tenderness with low values recorded for all treatment groups (<5kg F). This could be due to animals being slaughtered at a young age when there has been little accumulation of collagen and formation of crosslinking that increases toughness of meat (Young *et al.*, 1993). The cooking loss in this study was 36-38% which was higher than previously reported at 20-33% (De Brito *et al.*, 2016, De Brito *et al.*, 2015, Farouk *et al.*, 2007). The difference in cooking loss may be due to different sampling sites where loin muscles were tested in previous studies but this study tested on the semimembranosus muscle. The greater hue angle in lambs of the EARLY treatment indicates that the meat was less red. Although there is a statistical difference between the hue angle and cooking loss between treatments, these differences are not likely to be detectable by the customer and consumer therefore, are unlikely to be significant from the retail and eating quality perspective.

4.3 Limitations and future research

The main limitation of this this study was that it did not incorporate a fourth treatment of early weaning of lambs onto a ryegrass mix to allow for a more balanced comparison. The fourth treatment group was not included because previous research has shown that early weaning of lambs onto the ryegrass mix resulted in poor lamb growth (Rattray *et al.*, 1976) and therefore, this could have created an ethical issue in terms of animal welfare.

An additional limitation was that, the lambs were reared on grass for six weeks prior to slaughter (between 15 and 21 weeks of age) which may have diluted some of the effects of the forage and weaning treatments and future research should consider a longer period on the treatment diets with slaughter occurring directly off the treatments.

The experiment implemented a set weight slaughter policy with lambs >35kg being sent for slaughter at each of the two slaughter dates. This may have negated any observed growth, development and composition effects on the carcass but, is reflective of commercial practice.

Lastly, the dissection was only conducted on the hind leg and, therefore, may not be representative of the overall animal composition of the muscle and fat in the whole carcass. Ideally a whole carcass or a carcass side would be dissected however; this would take considerable time and resources that are not practical. Using the established method of hind leg dissection (Purchas et al 1991a) gives confidence that the results are reflective of carcass composition.

Further research is required to establish the effects of early weaning on the rumen development of lambs. This would allow us to understand if early weaned animals are able to utilise the highly digestible forages offered. A lack of rumen development could explain why only a small percentage of animals reached the target slaughter weight at the first slaughter date.

This study could also be further developed to determine the genetic difference for suitability for early weaning. It is possible that some breeds are better suited for coping with the stresses of early weaning compared to others. This would ultimately allow for an increased percentage of lambs achieving their target slaughter weight earlier thereby also increasing overall productivity of the farm.

4.4 Conclusion

This study aimed to investigate the effects of early weaning of lambs at 8 weeks of age onto herb-clover mix on carcass and meat quality characteristics in comparison to conventional weaning at 15 weeks of age.

Lambs can be weaned early at 8 weeks of age onto herb-clover mix to achieve similar carcass characteristics compared to lambs conventionally weaned at 15 weeks of age onto traditional ryegrass white clover pasture. Early weaning of lambs onto herb-clover mixes, however, could not match growth rates of lambs that were on herb-clover mix with their dams until 15 weeks of age. Nevertheless, when lambs were grown to a set weight for slaughter by allowing for a longer growth period, there did not appear to be any negative effect of early weaning onto herb-clover mix on lamb carcass characteristics of lean meat yield. Early weaning of lambs onto herb-clover mix also did not have negative effects on the lamb meat quality.

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