The nutrition and growth of lambs reared artificially with or without meal

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science

in

Animal Science

at Massey University, Manawatu, New Zealand.

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2017

Abstract

Jensen, A. (2017). The nutrition and growth of lambs reared artificially with or without meal. A thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Animal Science at Massey University, Manawatu, New Zealand.

Artificial rearing is routinely used in large-scale dairy sheep farms. One approach is to offer milk replacer (MR) and meal *ad libitum* to lambs. The aim was to evaluate the growth of female lambs in the first 12 weeks of rearing with (M) and without (NM) grain-based meal access (n=30/group) during four feeding periods. In period 1 (week 0-3), lambs were offered MR and meal *ad libitum*, and in period 2 (week 4-5) were transitioned outdoors onto pasture with continued access to MR and meal. Lambs were weaned off MR in period 3 (week 6-10), and meal in period 4 (week 10-12). The NM lambs received identical management, but meal was excluded. A treatment-by-time interaction was found whereby NM lambs had lower average daily gain (ADG) ($P<0.05$) in periods 1 (376±6 *vs*. 414±8 g/d) and 3 (146±7 *vs*. 241±7 g/d), no difference in period 2 ($P>0.05$), and higher ADG in period 4 (157±18 *vs*. -55±18 g/d, $P<0.05$) than M lambs. These results indicate that when lambs fed MR *ad libitum* are offered unrestricted access to good-quality pasture before weaning, meal may not be required to achieve a similar live weight at 12 weeks of age.

Data from the aforementioned experiment were further investigated by week to allow investigations of the relationship between nutrient intake and growth, describe variation in ADG in relation to environmental and feeding transitions, and to estimate pasture intakes, which were not measured. The different feeding transitions, nutrient intakes, and feeds were most likely causing the differences in ADG that occurred between treatment groups and weeks. The greatest variation in ADG of lambs occurred in the M lambs after meal

weaning, which was likely due to a poor adaption to a pasture-only diet. Pasture intakes were estimated by calculating lamb requirements for maintenance and growth from actual ADG and live-weight measurements, assuming that pasture intake made up the difference between actual intakes and theoretical intakes. It was found there were significant differences in estimated pasture intakes between M and NM lambs ($P<0.0001$) and intakes changed over weeks. In weeks seven, eight, and nine, M lambs were estimated to not consume any pasture, due to a high intake of meal, to achieve the observed growth rates. However, NM lambs consumed pasture over these weeks as pasture was their only feed source. These results allow speculation that pasture intake was very low in M lambs before meal was removed. It has been previously reported that high meal intakes when combined with low roughage intake can negatively impact rumen health and development, and transitioning from high meal to high roughage diets requires alterations in the ruminal microbe population and fermentation. The estimated low pasture intake before meal weaning, combined with the high meal intake recorded, may have contributed to the growth check that occurred once meal was removed, as lambs required a period to adapt to the pasture diet, as their rumen underwent the changes associated with transitioning between these diets. Further investigation into differences in pasture intake between lambs reared with and without meal, and more evidence as to what caused the growth check after meal weaning may allow further optimisation of different lamb-rearing systems.

Acknowledgements

I would like to sincerely thank my supervisors Sam Peterson and Patrick Morel (Massey University), and Sue McCoard (AgResearch) for their tireless help and guidance. I would like to thank the AgResearch-led Ministry of Business, Innovation, and Employment "Boosting exports of the emerging NZ dairy sheep industry" program for funding this research, in partnership with Kingsmeade Artisan Cheese, Maui Milk, and Spring Sheep Milk Co. I would also like to thank the Animal Nutrition & Physiology Team and Ulyatt-Reid Large Animal Facility staff from AgResearch Limited Grasslands for their assistance with animal care and data collection.

A great many thanks to Ajmal Khan, Frederik Knol, Catherine McKenzie, and David Stevens for their feedback and assistance in the writing of this thesis and analysis of results. I would also like to acknowledge the Lois Turnbull Postgraduate scholarship for personal funding.

Table of contents

List of tables

List of figures

List of abbreviations

a	Metabolisable energy requirement for maintenance
ADF	Acid detergent fibre
ADG	Average daily gain
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
b	Metabolisable energy required for growth
c	Crude protein
CMR	Milk replacer designed to be fed to calves
CP	Crude protein requirement for maintenance
CPI	Crude protein intake
CPgrowth	Crude protein that was required for growth (calculated for this trial)
CPmaintenance	Crude protein required for maintenance (calculated for this trial)
CPtheoretical	Calculated crude protein required to meet calculated maintenance and growth requirements
d	Crude protein required for growth
DM	Dry matter
DMI	Dry matter intake
g/d	grams per day
GE	Gross energy
K_g	Efficiency of utilisation of metabolisable energy for growth
Kg	kilograms
LMR	Milk replacer designed to be fed to lambs
LWT	Live weight
LWTend	Live weight at the end of the week
LWTstart	Live weight at the start of the week
ME	Metabolisable energy
MEI	Metabolisable energy intake

MEgrowth	Metabolisable energy that was required for growth (calculated for this trial)
MEmaintenance	Metabolisable energy required for maintenance (calculated for this trial)
MEtheoretical	Calculated metabolisable energy required to meet calculated maintenance and growth requirements
MJ	Megajoules
MR	Milk replacer
M	Lambs allowed meal
NDF	Neutral detergent fibre
NM	Lambs not fed any meal
OMD	Organic matter digestibility
P	Period
REML	Repeated-measure mixed-effects model
TCA cycle	Tricarboxylic acid cycle
VFAs	Volatile fatty acids

Chapter 1: A review of some of the factors affecting lamb growth in artificial-rearing systems.

1.1 Introduction

The New Zealand sheep dairy industry is currently undergoing significant growth, with farms ranging in size from less than 100 ewes to an estimated 20,000 ewes (Peterson and Prichard, 2015). As of 2015, the estimated worth of the industry was $13 million dollars (Peterson and Prichard, 2016), however, there is the opportunity for growth with the potential to become a billion-dollar industry (Griffiths, 2015).

In order to produce milk every year, ewes must become pregnant, and lambs produced are reared for replacements or sale. There are several different methods of rearing that are employed depending on farm size, infrastructure, input, and target outcome. In some systems, ewes raise their lambs until they are old enough to be successfully weaned (around 30 days) then milking begins, while in other systems ewes and lambs are separated for a period during the day and ewes are milked before reuniting them (McKusick et al., 2001). While both of these methods can be successfully applied on sheep dairy farms, very early removal of the lamb (less than four days of age) for artificial rearing is a common method used on large-scale farms to allow the most milk to be collected from ewes, and is the focus of this review.

Nutrition and growth of lambs are linked (Economides, 1986) and, therefore, feeding systems used in artificial rearing will affect the growth performance of lambs. The rearing period is an important time when the lamb transitions from a pre-ruminant to a ruminant, and the feed provided can affect lamb growth and rumen development, which affects post-weaning growth.

Dietary transitions during the course of rearing can result in periods of lowered growth (Manso et al., 1996), which can increase the amount of time it takes for lambs to reach a target weight, whether it is for sale, slaughter, or breeding (Litherland and Lambert, 2000). A better understanding of different feeding regimes for lambs within artificial-rearing systems may allow optimisation of systems for growth, systems that are better suited to the New Zealand setting, and more options for farmers to implement on farm depending on their farming objective. The purpose of this review is to discuss different factors that affect growth of lambs that are artificially reared, with a focus on nutrition.

1.2 Artificial rearing

Artificial rearing of lambs is carried out so that milk from ewes can be harvested and used for production or sale (McKusick et al., 2001, Sevi et al., 2009). In artificial-rearing systems, lambs are removed from their mothers one to two days after birth, and milk replacer (MR) is usually fed, either *ad libitum* or restricted, with meal (barley grain-based starter feed) and/or fibre sources provided (Lane et al., 1986). Milk is essential for lambs in early life and the amount of milk consumed and growth rate of lambs are often strongly related (Doney et al., 1984, Moffatt, 2002). However, in some studies, it has been reported that there was no significant effect of ewe milk yield on lamb growth (Duncan, 2012), or a weak correlation that may have been due to other factors such as lamb genotype (Muir et al., 2000). This may be due to ewes being capable of producing volumes of milk that are in excess of the lambs' requirements. Growth rates similar to those of ewe-reared lambs have been achieved by the feeding of MR *ad libitum* (Napolitano et al., 2008), and authors that report lower growth of lambs in artificial-rearing systems compared to natural rearing are reporting lamb growth from systems using restricted milk intake (McKusick et al., 2001). In addition to the differences in milk volume, differences in feeding frequency and diet composition may affect growth in different systems (Hernandez-Castellano et al., 2015).

What growth rates are possible in the New Zealand artificial-rearing system investigated in this thesis (feeding MR *ad libitum* and weaning lambs to pasture either with or without meal) are unclear due to a lack of research. Lambs' growth rates in overseas artificial-rearing systems (that fed MR *ad libitum*) have been reported to range from high growth (355±23 g/d) to lower growth (185±7 g/d) before weaning, thus it is around these numbers that discussion of high and low growth rates is based (Heaney et al., 1982, Penning et al., 1980).

Colostrum intake is important for lamb survival and growth (Hernandez-Castellano et al., 2014). Due to the structure of the sheep placenta, passive immunity cannot be transferred from the mother's blood via the placenta as occurs in some other species such as humans, and to a lesser extent dogs and cats (Chucri et al., 2010, Hernandez-Castellano et al., 2014), so lambs are usually kept with their mothers for one to two days after birth to allow them to obtain colostrum (Öztabak and Özpinar, 2006). Colostrum provides immunoglobulins to the lamb and transfers passive immunity, protecting the lamb from infection and disease (Öztabak and Özpinar, 2006). There were lower serum immunoglobulin concentrations, compared to that of lambs fed ewes' colostrum, as well as a higher mortality rate associated with feeding of artificial colostrum to lambs (Öztabak and Özpinar, 2006). Due to the close confinement of lambs in housed artificial-rearing systems, there may be rapid disease transmission, therefore, it is important to allow the lamb to obtain colostrum from the mother before removal to the artificial-rearing system.

Artificial-rearing systems are considered a high-cost method of rearing due to the costs of feed and labour (Lane et al., 1986). In dairy-calf production systems, the feeding of MR is more expensive than the cost of solid feeds, thus, early weaning is often carried out to reduce the cost of rearing (Eckert et al., 2015). Similarly, early weaning and/or restricted feeding of MR are often employed to reduce the costs of rearing lambs artificially (Lane et al., 1986). After weaning in many overseas artificial-rearing systems, lambs receive supplements when grazing, or are kept in fully or semi-housed situations (Dikmen et al., 2007, Heaney et al., 1984, Todorov, 2012). Lambs in New Zealand systems will often be weaned onto pasture, and there is currently a lack of information regarding performance of lambs weaned onto pasture from such New Zealand artificial-rearing systems.

1.3 Milk source and composition

Milk replacers can be manufactured from different milk sources, and the source and composition of MRs can affect lamb growth (Heaney et al., 1982, Owen and Davies, 1970). Lambs fed MR specifically designed to be fed to them (LMR) had higher weaning weights and higher growth rates compared to those fed a MR designed to be fed to calves (CMR) (216±7 *vs.* 185±7 g/d) (Heaney et al., 1982). Additionally, mortality was slightly higher for lambs fed on CMR compared to those fed LMR (17% *vs.* 15%) (Heaney et al., 1982). Cows' milk can also be fed to lambs, but greater growth rate can be achieved through feeding them whole ewes' milk (Owen and Davies, 1970). There are differences in composition of milks between these two species (Table 1.1). Sheep milk has higher protein, fat, and total solid concentrations than cows' milk (Park et al., 2007), thus, cows' milk may supply inadequate concentrations of these nutrients to achieve high rates of lamb growth. The composition of sheep milk also differs among breeds of sheep (Muir et al., 2000) (Table 1.1), and varies with the stage of lactation, feeding, and parity (Park et al., 2007), which may result in different compositions of MR, which may not meet lamb requirements.

Lactose is the major source of glucose for the pre-ruminant lamb (Chambers, 1984), and is responsible for a large provision of energy to the lambs that can be used for growth. Lactose also aids the absorption of minerals such as calcium and magnesium (Park et al., 2007). Thus, it is important the lamb is not deficient in lactose intake. However, there are no large differences in lactose concentration between ewe and cow milk (Park et al., 2007), so there are unlikely to be differences in lactose content of LMR compared to CMR. But lactose concentration does change over the duration of lactation, such that it is lower at the beginning and end (although the change is very small) (Park et al., 2007), so MR must be formulated to prevent changes in lactose content due to the stage of lactation from which milk is collected.

Another reason lower growth rates may occur in lambs fed MR compared to whole ewes' milk may be due to the nutrient composition of the MR failing to meet the lambs' needs, in terms of protein and fat (Mir et al., 1987). Proteins from another source are often substituted for milk proteins, which can increase the rate of emptying from the abomasum in calves, possibly resulting in lower utilisation of proteins (Guilloteau et al., 1981), and, when replaced with vegetable proteins, reduce utilisation due to lower apparent digestibility of vegetable proteins compared to milk proteins. Additionally, protein levels above 18% in MRs have no positive effects on growth of lambs and may have detrimental effects on lamb growth (Jagusch et al., 1976, Owen and Davies, 1970). These observations highlight that the origin of the milk or MR being fed to lambs can influence lamb growth rates.

Ewes' milk has a higher fat content than does cows' milk (Williams et al., 1976) (Table 1.1), and it is possible that the higher fat concentrations allow lambs to achieve greater growth rates due to the high energy density of fat (Owen and Davies, 1970), but, there is an optimal range of fat in MR; too much fat can lower lamb growth. The maximal growth rates were achieved when lambs were fed a diet containing 20-30% fat (Owen and Davies, 1970). The results of another study indicated that the optimal level of fat in LMR was between 25-35% fat, while, the maximal level of fat for a calf diet was 19% fat (Emsen et al., 2004). Apparently, lambs require more fat than calves, therefore, it is important to ensure that the MR being fed is suited to lamb requirements, as cows' milk is not suitable to support maximal growth of lambs.

Additionally, whole ewe milk contains growth promoters that are not present in MRs, which may partly explain why lower growth rates were observed when lambs were fed MR compared to whole ewes' milk (Hernandez-Castellano et al., 2015). And proteins from sources such as soybeans contain compounds that can retard growth and so must be removed before feeding (Walker et al., 1979), otherwise lamb growth may be affected. There are many other nutrients that are important to lamb growth, including fibre, minerals, and vitamins, and deficiencies in these can limit growth (CSIRO, 1990). However, it is beyond the scope of this review to discuss these nutrients and growth promotors.

While the highest growth rates in artificial rearing can be reached in lambs that are fed whole ewes' milk, the major reason they are removed from their mothers is to allow the sale or use of this milk for production of sheep milk products. Therefore, in lamb artificial-rearing systems, MR specifically manufactured for lambs should be used, but it is outside the scope of this study to compare the composition of commercial LMRs.

Table 1.1. Some published representative examples of the composition of ewes' milk and cows' milk

Reference	Species	Breed	Total solids %	Fat %	Protein %	Lactose %
(Williams et al., 1976)	Cow	Friesian	12.1	3.5	3.4	4.6
(Williams et al., 1976)	Ewe	Suffolk x Clun Forest	18.6	8.0	4.7	4.9
(Muir et al., 2000)	Ewe	East Friesian x Romney	20.4	8.4	5.8	5.5
(Morgan et al., 2006)	Ewe	East Friesian cross	-	8.4	3.9	5.9

1.4 Nutrient requirements

To achieve high growth, it is important that all nutrient requirements are met, but energy and protein requirements are considered the most important components to focus on, as they are often responsible for limitations in growth; a higher energy and protein intake allows higher average daily gain (ADG) (Brown et al., 2005). Energy is required for growth for both the substrates forming new tissue and meeting the metabolic requirement for growth (Millward et al., 1976), and protein is required for tissue deposition, and, thus, growth (Chambers, 1984).

The nutrient requirements of lambs have been previously published (ARC, 1980, NRC, 2007), however, the energy requirements for growth may have been underestimated and there is lack of data for requirements of young lambs before weaning (Danso et al., 2016). It is important to consider nutrient requirements to ensure that diets are formulated to allow high growth rates of lambs. Energy requirements of lambs have been assessed through fasting metabolic rate, maintenance requirements, and the energy costs of protein and fat deposition (Chambers, 1984), and there may be differences in requirements due to several factors such as breed, environment, and diet (Galvani et al., 2008). However, where nutrient requirements have been reported, these factors are not taken into account, which may result in differences between the recommended values and actual requirements. Nevertheless, nutrient intakes can be used to predict what growth may occur at different levels of intake, and conversely, requirements can be used to calculate what animals must have eaten to achieve the growth that was recorded.

1.5 Solid feeding, digestion, and growth

In many artificial-rearing systems, solid feed is provided to lambs at an early age to promote rumen development and prepare them for successful weaning from MR (Baldwin et al., 2000). Therefore, it is important to allow access to solid feed before weaning and to consider if there has been sufficient intake of this feed to allow development of the rumen before weaning, in preparation for lambs becoming reliant on solid feed to meet requirements for maintenance and growth.

Currently, there are different systems involving feeding solids before weaning and different combinations of meal and fibre (often pasture) are used. Meal is not required in natural rearing systems, but is commonly included in artificial-rearing systems to allow greater nutrient intake, growth rate (Bhatt et al., 2009, Poe et al., 1969), and rumen development, in particular, papillae development (Baldwin et al., 2004, Khan et al., 2016). Pasture is often included in ruminants' diets to promote an increase in rumen size and development (Baldwin et al.,2004), and allow lambs time to adapt to the diet that will be fed after weaning since, in New Zealand, lambs will be kept on pasture after weaning. Pasture is fed because feeding regimes during the pre-weaning period can affect the lamb's adaptation to post-weaning diets, and therefore affect the growth rate (Bhatt et al., 2009, Bimczok et al., 2005, Khan et al., 2016). However, it is unclear in systems involving feeding MR *ad libitum* and pasture before early weaning, whether meal is required for successful weaning.

1.5.1 Onset of solid intake

There is disagreement in the literature regarding the time of onset of solid feed intake in lambs. Lambs can begin to ingest solid feed when they are two to three days old, but in very small amounts (13-60 g DM/d pellet intake at nine days old) (Danso et al., 2014, Lane et al., 2000), with large intakes (250-300 g/d) occurring by the time they are 25 days old (in lambs weaned at 14 days old) (Lane et al., 1986). However, in other studies, it is found that lambs did not consume a quantity of solid feed that was able to be measured until 21 days of age (Geenty, 2010, Owen et al., 1969). The lambs in the experiment reported by Danso et al. (2014) were fed restricted milk volumes (120-210 g DM/d), and the lambs in the trial of Lane et al. (1986) were weaned when they were 14 days old, and so were reliant on solid feed to meet their demands. Therefore, it is possible the amount of meal or pellets consumed depends on the volume of MR fed, ability to digest the feed, and lambs' reliance on solid feed as a nutrient source to meet their requirements.

In natural systems, there are differences in solid feed intake depending on litter size; twins consume more solid feed sooner due to restrictions on milk availability compared to singletons (Geenty, 2010) and triplets begin grazing sooner than twins (Peterson et al., 2006), likely for the same reasons. Competition within litters will not occur in artificial-rearing systems that feed MR *ad libitum*, however, competition may be seen in lambs fed restricted amounts of MR. Lambs fed low amounts (366 g/d) of milk consumed more pasture by two weeks of age compared to lambs fed a higher amount (705 g/d), however, in both groups, intake of pasture at two weeks of age was very low (Joyce and Rattray, 1970). When weaning early, it is important to consider when lambs begin to consume solid feed, to ensure they can consume a sufficient amount to support growth after weaning (Walker and Hunt, 1981).

1.5.2 Different types of solid feed and composition

Milk replacer and meal are, to an extent, interchangeable in the diet once lambs have undergone some rumen development (Owen et al., 1969). In one experiment, as DM obtained from MR decreased, there was an increase in meal intake (Penning and Treacher, 1975). Similarly, Doney et al. (1984) reported that lambs that ingested less metabolisable energy from milk consumed more solid feed (as pasture) compared to lambs that received more metabolisable energy from milk. Additionally, the inclusion of meal in the diet can increase growth rate when the same volume of milk is fed, due to the higher nutrient intake (Danso et al., 2014).

The same effect of substitution can occur when feeding forage. It is suggested that there is an inverse relationship between milk intake and forage/solid feed intake (Doney et al., 1984, Joyce and Rattray, 1970). Lambs fed higher volumes of milk often had lower intakes of forage than did lambs fed lower volumes of milk (Penning and Gibb, 1979). The same trend was found by Joyce et al. (1970), with lambs fed low volumes of milk consuming significantly more pasture (9.31 kg DM/12 weeks *vs*. 7.17 kg DM/12 weeks) than lambs fed high volumes of milk. This may be due to gut fill in the lambs that are fed more milk, so there is less room for ingestion of forage, hence, the lower intake (Penning and Gibb, 1979). There may also be an effect of satiety; lambs may have received signals from distension of the abomasum due to a high milk intake, as there is a tendency for feed consumption to decrease as there is an increase in abomasal distension (Grovum, 1979). Lambs may also have received signals from satiety peptides and factors to lower voluntary feed intake (Woods, 2004). It is apparent that a high milk intake depresses the forage intake of lambs. An increase in the intake of pasture however, cannot compensate for the loss in milk intake during restricted feeding compared to feeding milk *ad libitum,* due to the lower energy density of pasture compared to milk (Doney et al., 1984). Milk generally forms the majority of nutrient intake in early life and forage intake increases to meet increasing appetite (Doney et al., 1984).

A high-energy and high-protein solid feed diet can improve ADG compared to a low-energy and low-protein diet. Feeding lambs a meal-based diet improved ADG compared to feeding lambs a high-forage diet, probably due to the higher metabolisable energy content (12.2 MJ ME/kg DM *vs.* 9.0 MJ ME/kg DM) of the high-meal diet (Haddad and Husein, 2004). There may also be benefits to feeding protein that has been protected from rumen degradation (Hadjipanayiotou et al., 1996), due to the requirement of protein for tissue growth. Both meal and forages can have proteins that are protected from rumen degradation. Different diets also supply different levels of nutrients, for example, meal is more energy dense than pasture (De Araújo et al., 2012), and so less must be consumed to meet energy requirements, while the metabolisable energy content of pasture is usually limiting performance (Litherland et al., 2002). However, whether it is protein or metabolisable energy that is deficient does not matter, because a restriction in either of these nutrients will result in low growth rates (Litherland et al., 2002). It may be concluded that inclusion of solid feeds can increase nutrient intake, however, the supply of nutrients differs between meal and pasture, which will affect growth rate.

1.5.3 Digestive tract development

When they are born, young lambs essentially have a monogastric digestive system and are termed pre-ruminants. The lamb must transition from the foetal stage to the pre-ruminant stage, then to the ruminant stage (Guilloteau et al., 2009). The change between pre-ruminant to the ruminant stage takes place over the artificial-rearing period, so it is important to consider the digestion changes that occur over this period.

The new-born's rumen compromises a considerably smaller proportion of the digestive system than the rumen in the mature animal (Figure 1.1). The abomasum in the pre-ruminant is a significantly larger proportion of the digestive tract compared to that in the ruminant. This is because milk digestion begins in the abomasum and does not enter the rumen; instead milk passes through the reticular/oesophageal groove directly to the abomasum (Baldwin et al., 2004, Ruckebusch et al., 1983) (Figure 1.1). The abomasal mucosa continues to increase in weight after birth, from day two to seven by 20-30% as this becomes very important for milk digestion, and then starts to decline in weight after the lamb is 21 days old (Guilloteau et al., 2009). This may be around the time or just after onset of solid feed intake, and, thus, rumen development, and this indicates the beginning of the transition to a ruminant and decreasing reliance on milk (provided milk and solid feeds are available).

[redacted]

Figure 1.1. The ruminant digestive system showing the four different compartments (rumen, reticulum, omasum, and abomasum) in new-born ruminants (A) and mature ruminants (B). The oesophageal groove is shown in the new-born system (A). Figures are not drawn to the same scale. Source: FAO, 2011.

1.5.4 Pre-ruminant and ruminant digestion

The end products of digestion in the pre-ruminant are: glucose, galactose, amino acids and small peptides, free fatty acids and monoglycerides (Chambers, 1984). There is a significant shift in the end products of digestion once the lamb becomes a ruminant, when the end products of digestion include a large proportion of volatile fatty acids (VFAs) and negligible glucose.

1.5.4.1 Carbohydrates

Products of carbohydrate metabolism are the largest source of metabolisable energy in ruminants (NRC, 2007), and, as previously discussed, metabolisable energy intake is an important determinant of the growth rate that can be achieved. Therefore, it is important to consider the digestion of carbohydrates in the ruminant. In pre-ruminants, fat from milk is the major source of energy, however, it is still important to consider carbohydrate digestion in the pre-ruminant, as this does contribute to energy intake.

There is a shift in metabolism as the lamb changes from the foetal stage to the pre-ruminant to the ruminant. Before birth, the foetal lamb obtained glucose directly from the mother (Leat, 1971). After birth, lactose obtained from milk or MR is broken down to glucose and galactose by lactase, and glucose is directly absorbed from the digestive tract (Chambers, 1984). Lactase is present in the digestive system before birth, and is essential once the lamb is born and reliant on digesting milk to obtain nutrients. The specific activity of lactase (IU/g protein) increases from day one to seven after birth then is lower again by day 23, when lambs may be starting to obtain some nutrients from solid feed, provided it is available (Guilloteau, et al., 2009).

Carbohydrate digestion in the rumen produces VFAs, so little starch enters the duodenum to be broken down to glucose, therefore, since there is little absorption of glucose, there must be a shift in hepatic metabolism. The ruminant must synthesise glucose in the liver via gluconeogenesis predominantly from propionate and glucogenic amino acids (Leat, 1971, Wolff and Bergman, 1972). However, glucose absorption from the small intestine remains possible if soluble carbohydrates escape rumen degradation and arrive in the small intestine.

Amylase is an enzyme, produced in the pancreas and intestinal mucosa, involved in the breakdown of starch (Owens et al., 1986). Pancreatic weight increases in the first week after birth by about 30% (Guilloteau et al., 2009), allowing greater secretion of enzymes. In new-born calves, the secretion of amylase is low, since there is little starch in the diet, but amylase concentration increases by 2400% by one month of age, and by 100% from one to four months (Guilloteau et al., 2009), and a similar pattern is seen in lambs (Ruckebusch et al., 1983). The rumen micro-organisms in a three-week-old lamb can digest starch, although the extent this occurs will depend on rumen development and microbial colonisation (Leat, 1971). Thus, it may be that there is some starch digestion in the rumen of young lambs and some starch digestion in the small intestine if it passes through the reticulorumen. Starch digestion is particularly important in lambs that have a diet that is high in meal.

After weaning, pancreatic amylase production increases so any starch that is not digested in the rumen can be digested to glucose in the duodenum (Guilloteau et al., 2009). Even in mature ruminants, some starch can reach the small intestine and be digested if the rate of passage is rapid enough to allow some starch to bypass the rumen (Lindsay, 1978, Owens et al., 1986), with 5-20% of starch consumed being digested in the small intestine in cattle fed a total mixed ration diet (Huntington, 1997). So, until the rumen develops, starch can enter the abomasum and small intestine and be digested. Thereby, providing nutrients to the lamb without significant fermentation capabilities of the rumen being necessary, which may allow significant glucose absorption from meal.

There is no limitation to starch digestion in the rumen, unlike the small intestine and large intestine (Ørskov, 1986). In cows fed a grain diet, ~10% of glucose is from direct absorption from the small intestine, with the remainder synthesised in the liver via gluconeogenesis

(Lindsay, 1978). But the composition of the diet can affect the amount of starch entering the small intestine, with around 90% of starch from oats, barley, or wheat digested in the rumen, when fed to mature ruminants, yet starch from corn has a slower rate of digestion, such that up to 40% can exit the rumen (Ørskov, 1986). But the amount that escapes the rumen is highly variable between animals, and feeding roughage can increase the amount of starch that escapes fermentation in the rumen (Ørskov, 1986).

The fermentation capabilities of the large intestine must not be dismissed. Around 100 grams of starch can be fermented to VFAs in the large intestine of mature sheep every day when there is continuous infusion from the ileum (Ørskov, 1986), such that any starch that is not digested in the upper digestive tract can be fermented in the large intestine, although how much starch will actually reach the large intestine is unknown (Thivend et al., 1980).

1.5.4.2 Structural polysaccharides

As forage is consumed, the ability to digest structural polysaccharides becomes important to allow utilisation of forages. Fermentation capabilities of the rumen are essential for the utilisation of cellulose and hemicellulose as a carbohydrate source. The majority of cellulose and hemicellulose digestion occurs in the rumen, but there is a minor amount of digestion and absorption from the large intestine. There are no cellulolytic enzymes produced by the sheep, therefore, they are reliant on microorganisms for their ability to utilise cell walls (Waghorn et al., 2007), and these microbes work to ferment cellulose and hemicellulose resulting in VFA production (Annison et al., 2002).

1.5.4.3 Volatile fatty acids

Fermentation of carbohydrates in the rumen results in the production of short chain fatty acids and, in particular, the VFAs: acetate, butyrate, and propionate. Fermentation of proteins also adds to VFA production, but to a lesser degree than carbohydrate fermentation (Van Houtert, 1993). Volatile fatty acids are the major energy source in the ruminant (Chambers, 1984), and are, therefore, a very important source of energy for growth, as the lamb transitions to become a fully-functional ruminant. The composition of the diet can affect the ratio of the VFAs produced, which can affect the development of the rumen in young lambs (See section 1.5.5), and can alter microbial protein production and efficiency of use of metabolisable energy. Microbial protein production and efficiency of use of metabolisable energy can be reduced as the ratio of acetate to propionate increases, as occurs with pasture compared to meal diets (Annison et al., 2002). Therefore, pasture may supply less metabolisable energy for lamb growth compared to meal, when the same volume of each feed is fed. This means not all metabolisable energy is 'equal', and there may be different utilisation of the energy consumed depending on the diet.

Because VFA formation relies on rumen fermentation, it is essential that there is rumen development and fermentation capability established before lambs become reliant on structural carbohydrate as a nutrient source to maintain a high growth rate (discussed in section 1.5.5). Volatile fatty acids are absorbed through the rumen wall into the blood, with some metabolism occurring in the epithelium, and are then used for different functions in the body (Van Houtert, 1993). Propionate is the major substrate for gluconeogenesis within the liver, while butyrate is metabolised to β-hydroxybutyrate and acetoacetate in the rumen epithelium, which are then metabolised in tissues for energy production (Van Houtert, 1993). In contrast, acetate does not undergo much metabolism in the rumen epithelium;

instead it is transported throughout the body to be used for acetyl CoA production to be used in lipid synthesis and tricarboxylic acid (TCA) cycle, and ultimately generating adenosine triphosphate (ATP) in tissues (Van Houtert, 1993). The VFAs are important for meeting lambs' energy requirements for maintenance and growth once they become a functional ruminant, and the ratio of VFAs produced differs between meal and pasture, which alters efficiency of energy utilisation and protein production, which in turn may affect growth.

1.5.4.4 Protein

A high protein intake is important in the growing animal, as proteins are necessary for tissue deposition and growth (Chambers, 1984). Milk proteins are the major source of protein in the pre-ruminant lamb; they are degraded to amino acids, which are then absorbed and used for protein synthesis (Walker, 1979). Digestion is initiated by pepsin in the stomach, and trypsin and chymotrypsin and pancreatic peptidases continue protein digestion in the small intestine (Kay, 1969).

As solid feed becomes a greater proportion of the diet and after weaning, there is a shift in protein source from MR to the solid feed. In the rumen, rumen-degradable protein sources are broken down to peptides, then amino acids, ammonia, and short chain fatty acids (Annison et al., 2002), and these precursors are then incorporated into rumen microbes, with ammonia being the main source of nitrogen for microbial protein synthesis (Kay, 1969). Microbial protein can then flow out of the rumen to the intestines, where it may be absorbed and utilised by the lamb (Annison et al., 2002). Ammonia that is not incorporated into microbial protein can be absorbed through the rumen wall (Annison et al., 2002), which can be used to synthesise non-essential amino acids in the liver or converted to urea in the kidneys and excreted or recycled, through secretion in saliva or direct entry to the rumen through the rumen wall (Kay, 1969). There is also outflow of endogenous proteins from the rumen and abomasum that may also be utilised as a protein source (Kay, 1969). The utilisation of ammonia and ruminal protein does not occur in lambs fed a solely milk diet, as milk does not enter the rumen, thus, milk proteins circumnavigate the rumen through the oesophageal groove (Kay, 1969).

In the adult ruminant, there can be bypass protein that enters the rumen but is not degraded there, and so can enter the small intestine. Condensed tannins and feeds with high fractional outflow rates may increase the amount of bypass protein (Kay, 1969, Kerr, 2010), and, therefore, increase the amount of protein supplied for metabolism. There are, therefore, three nitrogen sources that exit the rumen and they are undegraded proteins, microbial protein, and ammonia. Undegraded proteins and microbial proteins can be used as a source of protein to meet the maintenance and growth requirements of lambs.

1.5.4.5 Lipids

Fats are an important source of energy and provide highly energy-dense body reserves (NRC, 2007). The fat content of the diet of pre-ruminants is significantly higher than that of ruminants (due to milk fat content), thus, there may be more of a contribution by fat to energy supply in the pre-ruminant compared to the ruminant (Chambers, 1984). In functional ruminants, lipid digestion begins in the rumen, while in pre-ruminants, there is little lipid digestion before the small intestine, and in both cases, the absorption of lipids into the body occurs in the jejunum (Bauchart, 1993). Fats are required in MRs and different concentrations can be beneficial or detrimental to growth (see section 1.3), and in the lamb, can be a significant source of energy.

It may be concluded from the above sections relating to solid feeding that digestion and use of nutrients differs between the pre-ruminant and ruminant. It is also noted that there may be differences in products between pasture and meal diets and differences in efficiency of energy utilisation between these diets. However, whether meal makes any large difference to overall growth of the lamb when fed for a short period (less than 12 weeks), as occurs in most New Zealand artificial-rearing systems is unclear. Meal is included to promote rumen development, in addition to growth. Thus, rumen development is another factor to consider in the differences between pasture and meal diets.

1.5.5 Rumen development

The main factors affecting the ability of lambs to grow after weaning are the rumen size and the rumen's ability to utilise solid feed, therefore, adequate rumen development must occur prior to weaning to ensure a high growth rate after weaning (Joyce and Rattray, 1970). During rumen development, there are physical changes to the rumen, a change in animal metabolism, and a microbial population is established within the rumen. Rumen development is essential so that rumen microbes are present in sufficient numbers to be able to synthesise VFAs and for these to be absorbed into the animal, since in the mature animal VFAs are the primary energy substrate supplying greater than 70% of energy (Baldwin, 2000). The changes in anatomical components of the rumen are important to allow space for feed to be fermented, surface area for absorption of the products of fermentation, and for the series of movements associated with digestion, eructation, and rumination. The post-weaning nutrient intake of lambs weaned before any large amounts of rumen development occurs is significantly lower compared to their pre-weaning intake (Lane et al., 1986), and will result in a growth check. Provision of solid feeds to lambs increases rumen development, through both an increase in size of the rumen and greater total ruminal papillary surface area, and also causes an increase in the microbial population (Abou Ward, 2008, Baldwin et al., 2004, Wang et al., 2016). Therefore, they are included in diets to allow this development to occur before weaning.

The major increase in size and musculature of the rumen is largely promoted by the intake of a fibre source, while the major development of the ruminal papillae is promoted through fermentation end-products (Baldwin et al., 2004). It is the physical bulk of the fibre sources that promotes the increases in rumen musculature and weight, however, physical bulk alone cannot promote the growth of papillae (Baldwin, 2000, Baldwin et al., 2004), demonstrated by the presence of indigestible matter in the rumen (e.g., experimental sponges) not promoting morphological development of the rumen, but promoting growth in size of the rumen (Baldwin, 2000, Lane et al., 2000). For papillae development, fermentation capability must be established, indicating that nutrients and microorganisms must be present in the rumen for development to occur (Baldwin, 2000, Lane et al., 2000). The evidence for this is that infusion of VFAs directly into the rumen increased papillae development compared to lambs that had a saline solution infused (Lane and Jesse, 1997). Therefore, both a physical effect of solid feed in the rumen and fermentation of that feed is required to stimulate all aspects of rumen development.

Volatile fatty acid presence in the rumen is essential to stimulate morphological development. Different feeds can produce different molar proportions of VFAs from fermentation, which can alter development of ruminal papillae (Baldwin et al., 2004).

Forages tend to produce a higher proportion of acetate from fermentation, which does not stimulate papillae growth to the same extent as a higher proportion of butyrate and propionate would, as that which occurs with fermentation of meal (Baldwin, 2000, Khan et al., 2016, Lane et al., 1986). However, forages can still promote development of the ruminal papillae because they produce VFAs when they are fermented in the rumen.

Aside from the physical changes that happen during rumen development, several metabolic changes must also take place (Lane et al., 2000). There is increased oxidation of VFAs and ketone bodies begin to be produced in large quantities from butyrate as the rumen develops (Lane et al., 2000). There was large variation in individual lambs' rumen metabolic development, which was dependent on their intake of solid feed, indicating that metabolic development of the rumen is a function of solid feed intake (Lane et al., 2000). These metabolic changes are important for utilisation of solid feed from the rumen.

Rumen development can occur in lambs that are not fed solid feed. Milk can leak into the rumen when the oesophageal groove does not shut completely; the presence of milk can act as a substrate for microbes and promote development of the rumen papillae (Lane et al., 2000). Additionally, in calves, feeding milk can indirectly influence rumen development (Górka et al., 2011), however, development will not occur to the same extent as that in lambs consuming solid feed because there is less/lack of substrate entry into the rumen. Lambs maintained solely on milk show little rumen development in terms of capacity, weight, musculature development, papillary growth, and keratinisation, because of the lack of substrate in the rumen (Baldwin, 2000). Furthermore, lambs fed only milk do not have any significant change in the length and width of papillae (Figure 1.2), and papillae are significantly longer and wider in lambs which had been allowed access to solid feed in addition to milk (Lane et al., 1986). There must also be a large enough quantity of VFAs present and sufficient physical bulk of feed in the rumen to stimulate development (Baldwin, 2000), which does not occur with milk leaking into the rumen.

[redacted]

Figure 1.2 Change in number, width, and length of papillae in the rumen of lambs fed a milk-only diet to 84 days of age. Source: Lane et al., 2000.

It is unknown if there is a microbial colony in the rumen at birth, but it is known that establishment of or increases to an anaerobic microbial colony begins to occur just hours after birth; establishment of this colony is essential for rumen development and the lamb's ability to utilise fibre (Khan et al., 2016). Naturally reared calves (it follows that the same effect will likely be apparent in lambs) obtain microbes from their mother, the environment, and other animals, while in artificially reared calves, the microbes come from housing, handling, and are affected by the type of feed provided (although some microbes are transferred from their mothers during birth and early contact) (Khan et al., 2016). It may be that lambs reared in artificial-rearing systems have a different microbial population than that of naturally reared lambs, which may alter the fermentation pattern of VFAs, as can occur in kids (Abecia et al., 2014), although, more research into this area is required (Khan et al., 2016).

It can be concluded that meal and pasture stimulate rumen development in different ways, to different extents. However, it is unclear whether both feed sources are actually required in artificial rearing and whether diets that lack meal will cause less rumen development and lower growth rates once lambs are weaned to a pasture-only diet.

1.5.6 Transitions between solid feeds

The transitions from milk to solid feed and the importance of having an adequately developed rumen have been discussed above. However, after milk weaning has occurred, there is often also often a transition from meal and pasture to a pasture-only diet. Meal is included in diets to improve rumen development, but there are suggestions that high meal intakes combined with a low roughage intake can have negative effects on rumen development (Suárez et al., 2007), including lowering ruminal pH and causing plaque (mass of sticky cell and feed debris that adheres to papillae) formation, resulting in a less favourable environment for fermentation, absorption, and health (Castells et al., 2013), which may lower lamb growth and result in a slower transition to pasture.

The utilisation of forage may not be as great in ruminants that previously consumed large amounts of meal with little forage, likely due to lower ability to digest and consume as much forage (Khan et al., 2016), because there may not have been large increases in the size of the rumen due to a lack of dietary bulk to promote this. There may also be different rumen microbes that are present when changing from forage to concentrate diets (Khan et al., 2016). For example, there are fewer cellulolytic bacteria found in calves with a highly ground high-concentrate consumption, compared to those fed unground grains and forages (Beharka et al., 1998), which may affect the ease of a change between diet forms and may affect lamb growth over the transition period.

Additionally, there may be a period of behavioural adaptation when changing diets. Food neophobia is common in sheep introduced to new feeds, and they often avoid ingestion for several days (Van Tien et al., 1999). In one report, consumption of new feeds in adult sheep did not start until 14 days after the new feed was introduced (Chapple et al., 1987). This may occur with sudden introduction of any new feed into the lambs' diet, and result in a growth check. Thus, it may be concluded that there may be periods of lower growth, resulting from a poor ruminal environment and possibly feeding behaviour, when transitioning lambs between mainly meal to pasture diets, but there is little information in this area.

1.6 Volume of milk replacer fed

Restricting the supply of MR can either involve feeding restricted quantities of MR to lambs, or allowing access only for a limited period. Restricting MR is common in dairy-calf artificial-rearing systems (Khan et al., 2011), and is used in some lamb artificial-rearing systems. It is used as a tool to reduce the cost of artificial rearing (Manso et al., 1996) or to stimulate solid feed intake to allow an easier transition to the post-weaning diet (Khan et al., 2011, Khan et al., 2016). Restricting MR can be difficult in practice; lambs are in groups in pens, which reduces the costs of caring for the lambs and labour costs (Heaney et al., 1984), but causes some difficulties if accurate restricted milk feeding is desired. Automatic feeders with electronic identification of lambs would be required for accurate restriction of the MR to avoid some lambs consuming more than others, and although cafeteria feeders can be used to restrict MR, this is not as accurate. However, accuracy is not always required, and so this system may be used successfully if this is the case.

Lambs fed higher volumes (1255 kJ gross energy(GE)/kg $LWT^{0.75}$) of MR before weaning had lower intakes of solid feed after weaning compared to lambs fed the lower amounts (837 kJ GE/kg $LWT^{0.75}$) of MR (Manso et al., 1996). It was found that restricted MR feeding could be used without negatively affecting the lambs' solid feed intake and growth rates in the post-weaning period compared to the previous period, although the growth rates reported were very low compared to what is often recorded in other systems (ADG= 175±26 *vs.* 152±26 g/d, low and high allowance of milk respectively) (Manso et al., 1996). However, it is important to consider when the lambs are to be mated, sold, or slaughtered, as they do have a lower live weight at weaning than lambs that were fed more MR (5±1 *vs.* 7±1 kg live weight; weaned at 30 days; birth weight 2.7 kg), which takes time (less than 40 days) to correct (Manso et al., 1996). Lambs that have been fed restricted MR may, therefore, take longer to reach the target sale, slaughter, or mating weight, which is one of the reasons MR may be fed *ad libitum*.

Feeding less MR resulted in lower growth but, once solid feed ingestion was allowed, there were sharp increases in growth rates, due to increased intake of energy (Manso et al., 1996, Owen et al., 1969). Additionally, in the study by Owen et al. (1969), lambs fed restricted milk (275 g DM/d) had a higher growth rate immediately after weaning compared to lambs fed MR *ad libitum* (166 *vs.* -9 g/d), so there was no difference in overall growth between treatment groups over the experiment. However, the results of another experiment showed that lambs that were fed high volumes of milk (705 g DM/d) had final live weights that were 41% heavier than lambs in the group fed a low volume of milk (366 g DM/d) (Joyce and Rattray, 1970). There is variation in lamb growth among experiments (Table 1.2), which is possibly due to a number of factors that vary between experiments including breed differences, different environments, different metabolisable energy intake, and different weaning ages. The differences in results between studies may also be largely due to different levels of restriction or to differences in the post-weaning diet, which as noted above can affect growth.

Different digestibility of milk has been reported at different feeding levels. Digestibility of MR was lower for lambs fed high volumes of MR (1255 kJ GE/kg $LWT^{0.75}$) compared to those fed lower volumes (837 kJ GE/kg $LWT^{0.75}$), in terms of dry matter (DM), crude protein (CP), and gross energy (GE); it is thought that this effect was due to greater rates of passage in the lambs fed the higher amounts of MR (Manso et al., 1996). A greater rate of passage means more milk passes through the digestive tract quicker, thus, there is less time for digestion and absorption of nutrients from the MR. The lower digestibility of MR in lambs fed more is likely of little consequence, as they consumed more and had a higher growth rate than lambs fed restricted amounts of MR. Similarly, calves fed lower volumes of milk can fail to consume the same amount of digestible energy as those fed higher volumes, despite higher meal and hay intakes, and subsequently they had lower ADG (De Passille et al., 2011).

Feeding of MR *ad libitum* is common in artificial lamb-rearing systems due to the ease and greater growth performance that is commonly seen, but most studies have been conducted in overseas systems that do not wean to a pasture-only diet. Therefore, further investigation into lamb performance in different feeding systems that wean to a pasture-only diet and feed MR *ad libitum* is warranted for developing different lamb rearing systems in New Zealand.

Table 1.2 Average daily gain (ADG) of lambs fed milk replacer (MR) *ad libitum* or in restricted amounts.

MR feeding regime	Experiment	ADG (g/d)	MR allowance (g DM/day)	Weaning age (days)
Ad libitum	*Bimczok et al., 2005*	262±32	*Ad libitum*	37
	Penning et al., 1980	355±23	*Ad libitum*	28
Restricted	*Bimczok et al., 2005*	209±23	80-480 (increasing over experiment)	42
	Penning et al.., 1973	203±18	180	21
		254±18	248	21
		326±18	343	21
		221±18	180	29
		276±18	248	29
		321±18	343	29
		247±18	180	40
		287±18	248	40
		326±18	343	40
	Penning et al., 1980	239±9	247	28

1.7 Compensatory growth

Compensatory growth occurs after a period of nutrient restriction and is the subsequent growth rate compared to the previously low growth rate that occurred during the restricted nutrient period. For this to occur, the periods of nutrient restriction must be severe enough to cause very low growth rates of animals (Ryan, 1990). Compensatory growth can be affected by the age when the nutrient restriction occurs, the severity of the restriction, and the duration of the restriction (Manso et al., 1996, Ryan, 1990). The potential for compensatory growth may be affected by the body composition of the lamb at the time the diet restriction occurs (Iason et al., 1992). The mechanisms through which compensatory growth occur are reduced maintenance requirement, increased efficiency for growth and fattening, reduction in the energy of tissue deposited, and increased feed intake (Ryan, 1990). Immediately after a feed restriction ends, there are likely to be increases in weight gain seen that are due to an increase in gut fill (Ryan, 1990).

There is disagreement regarding whether compensatory growth occurs in animals fed restricted amounts of milk soon after birth. Some find that compensatory growth can occur once lambs on restricted intake of milk are weaned (Peters and Heaney, 1974b). This will likely occur to a lesser extent, or not at all, when these lambs are also provided with meal and a fibre source *ad libitum* before weaning. Others concluded that lambs that are restricted soon after birth will most likely be permanently stunted and will not undergo a period of compensatory growth (Ryan, 1990). The results of one experiment found neither compensatory growth nor permanent stunting in lambs that had restricted MR (Manso et al., 1996). Whether compensatory growth occurs, or lambs are permanently stunted may depend on the severity and duration of the restriction.

Growth performance in the pre-weaning period can have a significant effect on performance after weaning, and lambs with a higher weaning weight tended to have better growth rates after weaning (Bhatt et al., 2009). While there may be compensatory growth, it may not occur to the extent that would allow smaller lambs to achieve a weight closer to that of heavier lambs. However, compensatory growth is unlikely to occur in lambs fed MR *ad libitum,* regardless of whether they are fed solid feed or not, due to no real nutrient restriction being placed on lambs, but this is an important effect to consider in restricted feeding systems, as this may affect overall lamb growth.

1.8 Growth check

A growth check is when the growth rate slows, stops, or becomes negative (indicating loss of weight), which typically occurs when weaning lambs. There are several factors that can affect the duration and severity of the growth check. These are the volume of milk intake prior to weaning, the type of weaning (either gradual or abrupt), the post-weaning diet, the weight of lambs at weaning, the age of lambs at weaning, and the habitat. These are each discussed below.

1.8.1 Volume of milk intake

There is disagreement in the literature regarding the effects of volume of milk intake on the size of a growth check. Lambs fed a higher MR allowance (320 g DM/d) had a greater growth check at weaning than that of lambs on a more-restricted MR diet (180 g DM/d), and the growth rate of the restricted lambs was slightly higher after weaning compared to those fed more milk (Smith and Geenty, 1983). However, the authors of another study reported that there were no significant differences in the intensity and length of the growth check among lambs fed different volumes of milk (Manso et al., 1998). The lack of growth check in lambs on severe milk restriction may be due to little or no decline in nutrient intake at weaning, while lambs that are fed more MR may experience more of a decline in nutrient intake, due to losing the highly energy-dense MR from their diets, which results in a lower growth rate compared to the pre-weaning period. Thus, feeding MR *ad libitum* likely results in a significant growth check when lambs are weaned, however, there are other factors which can affect this, discussed below.

1.8.2 Type of weaning

There are two types of weaning that are used in systems of artificial rearing. They are gradual or abrupt weaning off milk. In gradual weaning, the volume of milk fed is decreased over a period of time, which has the effect of increasing the solid feed intakes of calves in preparation for their future diet of only solid feeds (Khan et al., 2011). In lambs fed milk *ad libitum* before weaning, there will be increases in solid feed intake over the gradual weaning period and, therefore, there will be a greater rate of development of the rumen, which may lessen the severity of the growth check once the milk feeding is stopped compared to abrupt weaning. In abrupt weaning, there is no decrease in the volume of milk fed prior to weaning; the supply of milk is simply stopped. This does not give lambs time to adapt to lower milk intakes by increasing solid feed intake, as occurs in gradual weaning. The growth check has been minimised by the use of gradual weaning in both lambs (Bimczok et al., 2005, Manso et al., 1996) and calves (Khan et al., 2011). Abrupt weaning from MR can result in a large growth check and the rationale behind gradual milk weaning is to avoid this and allow a smoother transition from milk to solid feed (Bimczok et al., 2005).

Gradual weaning is much closer to the system of weaning that naturally occurs compared to abrupt weaning. Average daily gains for 30 days after weaning were lowest in lambs that underwent abrupt weaning compared to lambs subjected to gradual weaning (126±52 *vs.* 207±48 g/d) (Bimczok et al., 2005), and the same effect was seen in calves (Sweeney et al., 2010). However, this may depend on the volume of milk fed prior to weaning, as calves that had high milk consumption prior to gradual weaning did not consume enough solid feed to support their growth during and after weaning, and so underwent a growth check (De Passille et al., 2011).

The growth check can be avoided by the use of gradual weaning, depending on management and feeding before weaning (Bimczok et al., 2005, Owen et al., 1969). Weaning type (gradual or abrupt) may have a greater effect on lamb performance than the prior milk-feeding regime (restricted or *ad libitum)*, as lambs that underwent abrupt weaning were lighter compared to lambs in the gradual-weaning treatment groups, whether they were restricted or fed milk *ad libitum* (Bimczok et al., 2005) (Figure 1.3), but weaning age may be a confounding factor as lambs were weaned at 12 kg rather than a specific age. While these effects have been reported in overseas systems, the possible different effects of gradual or abrupt weaning in a New Zealand pasture-based system are unknown, but are beyond the focus of this experiment.

The length of time over which gradual weaning takes place will have an effect on the amount of weight that is lost (if any). Restriction of milk one week before weaning increased the meal intake significantly in both the pre- and post-weaning periods, however, if lambs were to be weaned at 21 days of age (or less), there was no advantage in restricting the milk intake (Walker and Hunt, 1981), because there was little solid feed consumed over this period. Similarly, in calves, the length of gradual weaning can affect the growth check. Calves that were weaned over 22 days beginning at 19 days of age had a greater growth check than calves that were weaned over ten days starting at 31 days of age, however, the age at which gradual weaning began may be a confounding factor in that experiment (Sweeney et al., 2010). Therefore, it can be concluded from evidence in the literature that the growth check is dependent on the type of weaning that is carried out and the age at which it occurs.

Economically, in Germany, it was found to be cheapest to feed MR *ad libitum* and carry out abrupt weaning, despite the decreases in lamb performance (Bimczok et al., 2005), and it is the most practical method of weaning on a large scale (Heaney et al., 1984). Abrupt weaning decreases competition for milk if individual intake cannot be controlled. Therefore, it can be concluded that there are both advantages and disadvantages with either gradual or abrupt weaning systems, but either system can be successfully used.

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Figure 1.3. Weight of lambs from day 0 to day 28 after weaning for different weaning regimes. All lambs were weaned around 12 kg, therefore, there may be confounding effects of age. Abrupt: lambs were abruptly weaned from *ad libitum* milk replacer (MR). Limited access: access to MR that had previously been provided *ad libitum* was restricted by reducing the number of times lambs could feed over five days. Diluted: MR continued to be provided *ad libitum,* but milk powder was mixed at 100 g/L compared to previous concentration of 200 g/L. There was a significant difference between the abruptly weaned lambs and the other two groups. Source: Bimczok et al., 2005.

1.8.3 Post-weaning diet

The post-weaning diet can have an effect on lamb growth. Milk is an energy-dense feed, and the energy density of the diet lambs are being weaned on to may affect the growth check they undergo. A concentrate diet is more energy-dense than a pasture or forage based diet (De Araújo Camilo et al., 2012), therefore, weaning to a pasture diet may result in a greater growth check being observed compared to weaning to a grain-based diet, because there may be more of decrease in nutrient intake compared to when milk was available. Whether lambs have been previously exposed to the post-weaning diet may also affect the growth check, as there may be an adaptation period as the lambs become accustomed to their new diet (Van Tien et al., 1999). However, when meal is only included in lambs' diets for a short period after milk weaning, when ultimately being weaned to pasture, it is unclear whether there are beneficial effects to lamb growth beyond the meal-feeding period.

1.8.4 Weaning weight

After weaning, heavier lambs had a tendency to grow faster than lambs that were weaned at a lower live weight (Fraser and Saville, 2000). At weaning, the heavier lambs had a greater growth check than did the lighter lambs, the reason being that the lighter lambs received less milk, so there was less of a decline in nutrient intake and, therefore, less of a decrease growth rate was observed (Fraser and Saville, 2000). However, the heavier lambs (30 kg) still maintained a higher growth rate than that of the lighter lambs (20 kg), despite the greater growth check (286 *vs.* 255 g/d) (Fraser and Saville, 2000). Smith and Geenty (1983) reported that lambs weaned at 12 kg were significantly heavier up to 15 months of age (when the experiment ended) than lambs that were weaned at 9 kg (45 *vs.* 43 kg), but, weaning weight effects on growth rate may be confounded with the effects of different feeding levels and age. Therefore, it may be concluded that weaning weight can have a significant effect on post-weaning weights for a long period which may be of particular significance in any lambs that are to be kept as replacements, as this may affect their ability to be bred as hoggets.

1.8.5 Age at weaning

Some recommend that weaning should not occur before the lambs are six weeks of age as it may negatively affect growth, but this may not be viable economically, and lambs can be successfully weaned before this age (Heaney et al., 1984). Early weaning systems are reliant on adequate rumen development occurring before weaning (Economides, 1986), and weaning at a younger age probably results in a larger growth check, as development of the rumen is related to both intake of solid feed and age of the ruminant (Manso et al., 1996). Lambs that were older at weaning (28 days *vs.* 21 days) were heavier throughout the experimental period (up to 70 days of age) (Heaney et al., 1984). This effect is likely because lambs that are weaned at an earlier age may have less rumen development and so require time for rumen development to occur before they can utilise nutrients properly, and so subsequently have a large growth check (Lane et al., 1986). However, weaning lambs early (between four and six weeks) can be done successfully (lambs survive and have high growth rates after weaning), particularly when lambs are allowed access to high volumes of milk and good-quality pasture (Geenty, 1979), or solid feed before weaning, and is commonly used in artificial-rearing systems (Heaney et al., 1984).

1.8.6 Habitat

It has been suggested that weaning stress can be increased by a change in habitat, and so will reduce lamb growth, however, this was only seen to varying degrees depending on age at weaning (21 *vs.* 28 days) and type of MR (CMR *vs.* LMR) (Heaney et al., 1984). There was no difference in lamb live weights reported between those that remained in the pre-weaning habitat compared to those that were moved to a new habitat at weaning when fed LMR, but live weight (at day 70) was lower in lambs fed CMR and moved to a new habitat upon weaning at 21 days (16±0.3 vs. 18±0.3 kg), but not those weaned at 28 days (Heaney et al., 1984). Depending on the system of artificial rearing, it may be impractical to keep lambs in the same pre-weaning habitat, for example, if lambs are kept indoors for the entire milk-feeding period. It can be inferred that the habitat can influence lamb growth and is dependent on the type of MR used and the weaning age.

It may be concluded that there are several factors that can affect the growth check, including nutrition before and after weaning. The changes in growth that occur in different artificial-rearing systems are not well documented within New Zealand systems that eventually feed lambs only pasture. Therefore, more research into this area is required, however, investigating the effect of all of these factors on growth is beyond the scope of this thesis.

1.9 The effects of litter size and birth weight on growth

There are many different factors that affect the birth weight of lambs, including maternal age, nutrition, season of birth, genetics, altitude, and litter size (Gootwine and Rozov, 2006, Gootwine et al., 2007). The East Friesian (a common dairy sheep breed) often produces multiple lambs. With higher litter sizes, there is a tendency for lower foetal weight as the two are linked, because of the effects of maternal constraint and the placental mass per foetus (Gardner et al., 2007, Gootwine et al., 2007, Manso et al., 1996, McCoard et al., 2000). Birth weights of lambs born as quadruplets or more were not significantly different from birth weights of triplets, however, the birth weight of single, twin, and triplets were all significantly different from each other (Heaney et al., 1982), but, this is not always the case. Therefore, litter size can also have an effect on growth through birthweight effects.

Multiples reared by a ewe had significantly lower growth rates compared to multiples that were artificially reared and fed MR *ad libitum* (Lindahl et al., 1972). This difference in growth rate is due to the better nutrition of multiples in artificial-rearing systems; when raised by their mother, these lambs will not be able to achieve the same nutritional intake due to competition from their siblings (Lindahl et al., 1972). However, more recent studies comparing multiples' growth in natural rearing with artificial rearing could not be found and would be required before it could be concluded that growth rates differ between multiples in these two systems of rearing. This is because overall differences in lamb growth between artificial and natural rearing have not always been found (McKusick et al., 2001).

Peters and Heaney (1974a) found that lambs born as twins and reared as singles grew at rates similar to those born and raised as single lambs, in contrast, Morgan et al. (2007) reported that twins raised as singles had a lower growth rate than lambs that were born and raised as singles, but the twins were only growing on average 18±17 g/d less. In artificial rearing, there may be less competition between siblings for milk, while lambs raised as multiples by their mothers have a significant disadvantage, in terms of growth rate, compared to singles (Peters and Heaney, 1974a). Competition can occur in systems of artificial rearing, particularly in restricted-feeding systems; in calf systems, there is increased competition when fewer teats are available than the number of calves (one teat to three calves) (Von Keyserlingk et al., 2004).

Birth weights were lower as there were more lambs born per litter, however, at weaning (six weeks) there was no longer any significant difference between body weights of single or twin lambs that had been artificially reared (9.9±0.7 *vs.* 9.1±0.6 kg; four weeks old at weaning; birth weight was 3.9 kg) (Emsen et al., 2004). But, in another study, single lambs did have a tendency to undergo a shorter growth check at abrupt weaning than did twins (9.9 days compared to 12.9 days, respectively) (Lane et al., 1986). Despite the litter size affecting the birth weight of lambs, it does not always appear to affect the growth rate (Lindahl et al., 1972). However, not all studies reached the same conclusion. There were differences in growth rates of lambs from different sized litters found by Bimczok et al. (2005), in which, single lambs (246±40 g/d) that were artificially reared had greater growth rates than did twins or triplets (219±29 g/d) despite being artificially reared and allowed the same volume of feed. Thus, growth rate may differ depending on litter size, and this may be due to a number of differences between experiments including breed, birth weights, and diets.

In the first week after birth, a higher digestibility of MR is associated with a higher live weight of lambs compared to that of lambs of a lower live weight (Houssin and Davicco, 1979). Lambs with higher birth weights are capable of digesting MR to a greater extent than lighter lambs, so lambs with low birth weights are restricted by digestive ability initially (Greenwood et al., 1998). Light lambs may require additional time to adapt to the diet which differs from the supply of nutrients the foetus received (the post-natal diet (milk) is relatively high in fat and low in carbohydrate compared to the foetal diet) (Greenwood et al., 1998), possibly because lighter lambs may have had restricted growth *in utero*, which can lower gastrointestinal tract function and development (Trahair et al., 1997). These digestive ability differences may be partly responsible for the lower growth rate in lighter lambs compared to that of heavier lambs.

Lambs with high birth weights, fed *ad libitum*, were initially faster growing than lambs with low birth weights (345±14 *vs.* 329±15 g/d) (Greenwood et al., 1998), possibly for the reasons discussed above. Additionally, lambs with low birth weights have lower efficiency of energy utilisation for tissue deposition and have limited ability to synthesise new muscle protein and, therefore, limited ability for large amounts of muscle growth because they are born with fewer myonuclei (Greenwood et al., 1998, Greenwood et al., 2000). Subsequently, it is predicted that these lambs may have smaller muscles when they reach their mature size (Greenwood et al., 2000). The nutrient supply of the foetus can affect growth, and when the requirements for growth are not met there can be a negative effect on muscle growth (McCoard et al., 2000). Myofibre size in twin lambs was 23% lower compared to that in single lambs (McCoard et al., 2000), possibly restricting the muscle growth potential. Additionally, Greenwood et al. (1998) found that bone mass of lighter lambs may not have the capacity to grow to the same extent and match that of heavier lambs. It may be the lower protein deposition and lower bone mass differences that explain why lambs that are lighter at birth initially grow slower. Another possibility is that there is not (or not entirely) a physiological reason, rather a mathematical reason. As growth is exponential after birth (Gbangboche et al., 2008), lighter animals grow slower than heavier animals because their growth potential is lower than that of the heavier animals.

Birth weight has an effect on DM intake; lambs that are heavier at birth consume more feed, which may contribute to the higher growth rate recorded in these lambs (Penning et al., 1980). However, Greenwood et al. (1998) reported that light lambs can have greater weight-specific intakes (intake as a proportion of body weight). Although, because of the possible lower muscle protein synthesis and reduced efficiency of tissue deposition in light lambs, it is unclear if the higher weight-specific intake can translate to a higher growth rate compared to heavy lambs.

Birth weight may affect the onset of solid feed intake and the ability to successfully wean lambs early. Lambs that were heavier at birth and weaned at 21 days of age consumed more meal than lambs that had a light birth weight (less than 1.6 kg), however, those that were not weaned until 42 days old, did not have any differences in meal intakes (Walker and Hunt, 1981). Additionally, solid feed intake was found to be negligible until the low-birth-weight lambs were 28 days old, which was later than that of the lambs with higher birth weights (Walker and Hunt, 1981). Birth weight had no effect on the growth check that occurred at weaning in one trial of lambs weaned very early (14 days old) (Lane et al., 1986), but, lambs with low birth weights were more likely to die, usually due to starvation, as a result of early abrupt weaning, because those lambs failed to gain enough weight/sufficient body reserves for successful weaning to occur (Walker and Hunt, 1981). Therefore, lambs with low birth weight need weaning to be delayed so they can reach an appropriate live weight (with enough body reserves to support them over the dietary transition) and age and can thrive on solid feed when the milk supply is stopped; they do not have significant rumen development, solid feed intakes, and sufficient body reserves to support them once weaning occurs if they are weaned very early. In conclusion, there are differences in lamb growth between litter sizes and different birth weights. It is unclear if these growth differences are an issue when lambs are fed MR *ad libitum* and when lambs are weaned after significant intakes of solid feed can occur. These effects must be considered when evaluating lamb growth in artificial-rearing systems as differences in birth rank and litter size may cause differences in recorded growth rate.

1.10 Sex effects on growth

At birth, male lambs are heavier than female lambs (Heaney et al., 1982, McKusick et al., 2001, Peters and Heaney, 1974a). The reasons for this may be due to male lambs having higher cotyledon weight (but not number) than female lambs, possibly allowing greater nutrient supply to the male lamb (Rhind et al., 1980). The presence of Mullerian-inhibitor substance and androgens may allow male lambs to grow faster *in utero* (Gardner et al., 2007). However, it is reported elsewhere that androgens may not have any significant effect on growth until after lambs are two months old (Stapleton et al., 1980).

Some experiments have shown that sex does not alter the weaning weight, growth rate, or the growth check (Heaney et al., 1982, Lane et al., 1986, Lindahl et al., 1972). Similarly, Manso et al. (1996) reported that in the pre-weaning period, there was no difference in the growth rate (103±31 *vs.* 99±31 g/d) of male or female lambs. However, female lambs had greater growth checks than did male lambs (3 vs 2 days), but, there was no difference in growth rates after the growth check had occurred (Manso et al., 1996), and the significance of this check is debatable. In natural rearing, male lambs had higher growth rates than did females, but in artificial rearing, no differences in growth rate have been observed until lambs were 70 days old, when males had a higher growth rate than that of females (McKusick et al., 2001, Peters and Heaney, 1974a), which may be due to androgens starting to have a significant effect on growth. Male lambs had higher growth rates than female lambs (254±5 *vs*. 236±5 g/d) after weaning at 28 days, and because the male lambs grew faster, they had a higher feed conversion efficiency than that of the female lambs (Penning et al., 1980). Similarly, castrated male lambs have also been found to grow faster than female lambs (290±11 *vs*. 260±11 g/d) (Penning and Treacher, 1975). Thus, there is no agreement on whether male lambs grow faster or at the same rate as female lambs. This may be due to breed differences in growth, different weaning ages and time over which the growth rates are calculated, or different feeding systems used among experiments. Females are important in sheep dairy farms, as they can go on to enter the milking flock, and it may be that they grow slower than the males that are being reared, so when investigating growth of lambs in artificial rearing, it must be remembered that there may be differences in growth rate due to sex.

1.11 Breed

There are distinct dairy sheep breeds such as the East Friesian, Awassi, and Lacaune. These were developed overseas and are now found in New Zealand milking flocks. Breed has an effect on the growth rate of lambs, and birth weight can be affected by breed, which may, in turn, affect the growth rate (Shrestha et al., 1982). The growth rate may also be partially inherited from parents (Thrift et al., 1973), thus, the growth rate may differ between breeds and individuals. Breeds imported from overseas may have different reported growth rates compared to what may be observed in New Zealand due to different management and conditions. Heterosis can also improve growth rates and so may allow a greater growth rate to be achieved than that of pure-bred animals (Dickerson and Lasted, 1975). There is little information about the growth of lambs reared artificially in New Zealand. When conducting research into this area, because of differences in growth rates between breeds, it is important to use common breeds that will be or are reared artificially to investigate growth.

1.12 Post-weaning growth

After weaning, lambs fed on a restricted diet (80-480 g DM/d) before weaning had higher growth rates compared to lambs that had been fed milk *ad libitum* (192±53 *vs.* 137±57 g/d) (Bimczok et al., 2005). However, age may have been a confounding factor in the study because lambs were weaned at 12 kg rather than at a specific age, so lambs fed restricted diets were older at weaning. But, by day 70 there was no significant difference between the growth rates of the lambs fed on either amount of milk feeding (204±27 *vs.* 201±25 g/d) (Bimczok et al., 2005).

Lambs with low growth rates and live weights before weaning may be a problem in the New Zealand system. Pasture does not provide large amounts of energy for growth (Litherland et al., 2000), therefore, lambs may take a longer time to reach the target weight than when being fed meal. When feeding meal in a feedlot, lambs have a much higher growth rate than lambs fed ryegrass pasture (325±34 *vs.* 89±34 g/d), and this is likely due to lower energy intake of lambs fed pasture (Murphy et al., 1994). However, the growth rate observed on pasture in that experiment is much lower than that which has been reported for lambs in New Zealand when weaned to pasture (greater than 400 g/d) (Thomson and Muir, 2009). Animals that are grazing pasture also have greater maintenance requirements than animals consuming a total mixed ration (TMR) on a feedlot due to the metabolic cost of their grazing activity (Dıaz et al., 2002). High growth rates are the target as they result in less total feed and maintenance feed required to reach the same weight, meaning lambs with higher growth rates are more efficient (Litherland and Lambert, 2000, Muir et al., 2003). A wide variety of post-weaning growth rates which are variable across experiments has been reported (Table 1.3). The variability between experiments may be due to a number of factors including different weaning age, pre-weaning diet, post-weaning diet, (Table 1.3), health, environmental conditions, and lamb breed, all of which may cause differences in growth rates to occur among experiments. These results, whatever the cause, indicate that the post-weaning diet, in addition to the pre-weaning diet, can have an effect on the growth of lambs. But, what growth occurs in dairy-lamb rearing-systems involving only high-quality pasture feeding, when weaning early after feeding MR *ad libitum*, compared to pasture and meal feeding has not been investigated.

Table 1.3. Post-weaning average daily gain (ADG) of lambs that were fed different levels of milk replacer (MR) before weaning.

MR feeding regime	Experiment	Post-weaning ADG/ g/d	Post-weaning diet	Weaning age (days)	Prior MR allowance (g DM/day)
Ad libitum	*Bimczok et al., 2005*	137±57	Hay and pellets	37	*Ad libitum*
Ewe reared	*Murphy et al., 1994*	325±34	Meal	Not specified (28 kg LWT)	Ewe reared
	Murphy et al., 1994	89±34	Ryegrass	Not specified (28 kg LWT)	Ewe reared
	Geenty et al., 1985	96	Ryegrass	28	Ewe reared
	Geenty et al., 1985	182	Ryegrass	84	Ewe reared
	Geenty et al., 1979	177-329	Ryegrass	28-42	Ewe reared
Restricted	*Bimczok et al., 2005*	192±53	Hay and pellets	42	80-480
	Penning et al., 1973	307±18	Hay and meal	21	180
		292±18	Hay and meal	21	248
		212±18	Hay and meal	21	343
		329±18	Hay and meal	29	180
		362±18	Hay and meal	29	248
		338±18	Hay and meal	29	343
		405±18	Hay and meal	40	180
		392±18	Hay and meal	40	248
		206±18	Hay and meal	40	343

1.13 Conclusion

This review has investigated different aspects of artificial rearing systems for lambs, focussing on the nutrition and growth of lambs within different systems. There are many different factors that affect lamb growth within artificial-rearing systems, from nutritional factors to management of lambs within these systems. Because the sheep dairy industry is relatively new to New Zealand, there are many unanswered questions about artificial rearing within a New Zealand farm system context. There is a variety of artificial-rearing systems that feed different milk volumes to lambs, feed different solid feeds, and wean at different times currently in use on different farms. One of the key differences between the current New Zealand system and most overseas systems is that lambs may ultimately be fed a pasture-only diet or a pasture-based diet. Therefore, further investigation of growth around weaning onto pasture is required, particularly for the dairy sheep breeds that are used.

1.13.1 Objectives

The purpose of this research is to increase knowledge around different artificial lamb rearing methods in a New Zealand pasture-based setting. This research will benefit farmers that employ, or will employ, artificial rearing of lambs and allow them to apply a system optimised for lamb growth.

The objective of the trial described in chapter 2 was to evaluate whether it is necessary to include meal in lambs' diets to maintain high pre- and post-weaning growth rates, when they are being fed MR *ad libitum* and given early access to pasture. The system including meal is currently used, and this research aimed to investigate if the system could be simplified by eliminating meal without detrimental effects on lamb growth.

The findings of chapter 2 led to some interesting results of growth around weaning that warranted further investigation. Therefore, the objective of chapter 3 was to investigate the relationship between nutrient intake and rate of lamb growth between treatment groups and different environmental and weaning transition periods in more depth using the experimental data from chapter 2. A further aim of chapter 3 was to estimate pasture intakes (which were not be measured) by calculating theoretical intakes required to meet maintenance and growth requirements that were calculated from observed growth rates and live weight. The final objective of chapter 3 was to describe variation among ADG of lambs. This research was conducted to investigate if an artificial lamb-rearing system currently in use could be simplified to just a MR and pasture input without compromising lamb growth.

Chapter 2: How does feeding meal affect growth of artificially reared East Friesian-cross dairy lambs?

2.1 Introduction

The New Zealand sheep dairy industry is currently experiencing significant growth (Peterson & Prichard 2015). In the first 30 days of lactation, when lambs would normally be suckling, dairy ewes produce around 25% of their total milk yield, so artificial rearing of lambs is used on some farms to enable this milk to be harvested and sold (McKusick at al., 2001). One artificial rearing system that is used for lambs in New Zealand involves feeding milk replacer (MR) and meal *ad libitum*. Feeding meal or other solid feeds during the pre-weaning period can improve the lamb's adaptation to diets after weaning off milk and improve subsequent average daily gain (ADG) (Bimczok et al., 2005). Thus, the rationale behind feeding meal is that it allows earlier intake of solid feed and rumen development when lambs are reared indoors without pasture access.

The main factor affecting ability of lambs to grow quickly after weaning off milk is their rumen's ability to utilise solid feed (Joyce & Rattray, 1970). Once lambs are weaned off milk, they rely on their rumen to ferment solid feeds and for absorption of volatile fatty acids (VFAs). Mature ruminants obtain approximately 70% of their energy from VFAs (Baldwin, 2000), making it essential that lambs have a well-developed rumen that is capable of producing sufficient VFAs to support high ADG. In young ruminants, the amount of solid feed eaten and its composition (the quality and quantity of carbohydrates and proteins) dictate various behavioural, morphological, and physiological developments and, thereby, determine the success of the transition from milk to post-weaning diets (Khan et al., 2016). However, it is unclear how meal offered to lambs during the pre-weaning period affects their growth performance during transitions from milk to pasture. The aim of this experiment was to compare the growth performance of artificially reared lambs fed MR *ad libitum*, with and without access to meal during transitions from MR to pasture, when given early access to unrestricted pasture.

2.2 Materials and methods

All procedures of this study were approved by the AgResearch Grasslands Animal Ethics Committee, Palmerston North, New Zealand.

2.2.1 Experimental design

This study was conducted at AgResearch Limited Grasslands in Palmerston North, New Zealand. East Friesian cross-bred lambs (n=60, three-day-old females) were sourced on the same day from a commercial farm and allocated to two groups (n=30/group) balanced for litter size (50% singles/twins and 50% triplets/quads) and average initial weight (4±0.2 kg). Lambs were sourced at three days old to allow them time to obtain colostrum from their mothers. Meal lambs (M) were given access to meal *ad libitum* from weeks 0 to 9 of the experiment, whilst lambs fed no meal (NM) received identical treatment except meal was excluded from their diets. There are three key transition phases in current artificial lamb-rearing systems in New Zealand: moving outdoors, weaning off MR, and weaning off meal. To study these transitions, the experiment was divided into four periods. In period 1 (week 0-3), lambs were housed in an indoor temperature-controlled facility, with one pen of 30 lambs per treatment, and were allowed access to MR *ad libitum* (Anlamb, NZAgbiz Ltd, Timaru, New Zealand; mixed at 230 g/L) fed through an automatic feeder (CalfMom ALMA Urban Feeder, PPP industries, Tuakau, New Zealand) with one teat per pen. Individual intake of MR was recorded electronically and checked twice daily to ensure lambs had learned to use the automatic feeders and to identify any potential health issues that may be causing low intake. Additionally, while lambs were indoors, each lamb had an individual daily health check (i.e., incidence of lameness, bloat, navel infection, scours, and eye infections). All lambs survived although one lamb was treated for pneumonia and several treated for eye infections.

Lambs fed meal were offered grain-based TLC lamb meal *ad libitum* designed by Animal Innovations Pty Ltd (Totness, South Australia 5250) and manufactured by Gavins Grain Ltd (Gordonton, Hamilton, New Zealand). A textured meal without a forage source was used and consisted of soy and canola meal, maize and barley grain, molasses, vegetable oil, and lamb additive mineral mix (details not available in addition to chemical composition). Meal was provided in feeders along the edge of the pen providing 20 cm head space per lamb and was replaced daily. In period 2 (week 4-5), after three weeks indoors, lambs were moved outdoors onto ryegrass and white clover pasture into three cohorts per treatment (n=10/cohort) organised into three blocks with one pen per treatment in each block. Over this period, each cohort was fed MR *ad libitum* through one cafeteria feeder with four teats. Each morning and afternoon, the feeder was cleaned, and new MR was provided. Over this period, M lambs continued to be provided meal *ad libitum* in troughs. Lambs were abruptly weaned from MR, as occurs in the large-scale lamb-rearing system being investigated, at the end of period 2 on day 38. In period 3 (week 6-10), M lambs continued to have access to meal *ad libitum* until week 9, at which point they were gradually weaned from meal. Meal provided was reduced by 10% of *ad libitum* intake per day for ten days over weeks 9 and 10 (all meal removed by day 68). In period 4 (week 10-12), both groups received unrestricted access to pasture until week 12 when the experiment ceased.

2.2.2 Animal and feed measurements

In Period 1, lambs were fitted with electronic identification collars that allowed individual daily MR intakes to be recorded by the automatic feeder, and group meal intake was recorded daily by refusals. In period 2, cohort MR intake was recorded daily by refusals and in period 2 and 3, cohort meal intake was recorded daily by refusals. Lambs were allowed access to water *ad libitum* at all times. Lambs were weighed at the beginning of the experiment without fasting and weekly thereafter at the same time of day. Samples of MR and meal were taken weekly and pooled for analysis to give a representative nutrient profile of the feeds over the experimental period. Composition of the MR was determined by the procedures of AOAC (1990) (Nutrition Laboratory, Massey University, Palmerston North, New Zealand). Composition (dry matter (DM) basis) was: 96.4% DM; 5.8% ash; 25.6% crude protein (CP); 25.5% fat; 21.6 MJ/kg metabolisable energy (ME). Composition of meal was evaluated using near-infrared spectroscopy (NIR) (RJ Hill Labs, Hamilton, New Zealand). Composition (dry matter basis) was: 87.2% DM; 17.0% CP; 4.7% ash; 4.1% fat; 2.7% nitrogen; 12.3% neutral detergent fibre; 5.9% acid detergent fibre and 14.0 MJ/kg ME and 92.1% organic matter digestibility. Metabolisable energy was calculated using AFRC (1993) and Lincoln University standard formulae. Pasture samples were taken weekly after lambs were moved outside. Ten random cuts using a 0.25 m x 0.25 m quadrant were taken from each paddock. Samples from each cohort were pooled for weeks 4-5 (period 2), weeks 6-9 (period 3), and weeks 10-12 (period 4) and underwent NIR analysis to determine composition (Table 2.1) (Nutrition Laboratory, Massey University, Palmerston North, New Zealand). Feed samples were collected in these periods to allow any changes in nutrient composition over the different transition periods to be observed. Pasture intake was not able to be measured but plate-meter readings were taken to give an indication of allowance. Thirty plate readings were taken in each cohort paddock weekly and there was usually no large difference between groups. Pasture allowance was between 1700 and 5000 kg DM/ha over the experimental period.

Table 2.1 Composition of pasture grazed by lambs in two treatment groups (meal feeding (M) and no meal feeding (NM)) over three periods of milk and meal (M lambs) or milk feeding (NM lambs) (period 2), pasture (NM) or pasture and meal feeding (M) (period 3), and pasture feeding only in both groups (period 4).

Nutritive component	Treatment group	Period 2	Period 3	Period 4
Dry matter (%)	M	17.1	16.7	16.9
	NM	17.1	16.4	15.1
ME (MJ/kg DM)	M	11.9	11.0	11.2
	NM	11.9	11.1	11.3
Crude protein (%)*	M	22.7	21.5	15.5
	NM	25.2	21.6	20.6
Ash (%)*	M	10.7	9.7	8.6
	NM	10.9	9.8	10
NDF (%)*	M	41.0	41.1	43.2
	NM	38.8	43.5	37.9
ADF (%)*	M	18.4	19.8	22.8
	NM	18.0	20.5	19.1
OMD (%)*	M	83.9	79.6	79.4
	NM	83.5	78.2	83.3

M= meal group; NM= no meal group; ME=Metabolisable energy; NDF=Neutral detergent fibre; ADF=Acid detergent fibre; OMD=Organic matter digestibility. *=as a percentage of DM. Composition was determined by NIR analysis (Nutrition Laboratory, Massey University, Palmerston North, New Zealand).

2.2.3 Statistical analysis

A repeated-measure mixed-effects model was fitted for ADG with fixed effects of period, birth rank, and treatment group, and random effects of lamb nested in pen within block, with initial live weight fitted as a covariate. Lamb live weight at the end of each period was analysed by fitting a repeated-measure mixed-effects model and data were log-transformed to meet the assumptions of normality and homogeneity. Included were fixed effects of period, birth rank, and treatment group, and random effects of lamb nested in pen within block, with live weight at the beginning of each period fitted as a covariate. These analyses were conducted using R (R Core Team, 2016). All other analyses were completed using GenStat 18th edition (VSN International, 2015). Two statistical programs were used due to different functionality being available in the different programs. MR intake for period 1 was analysed by analysis of variance (ANOVA) with fixed effects of birth rank and treatment group, and initial live weight used as covariate. Data for MR intake in period 1 were log-transformed to meet the assumptions of normality and homogeneity. Average MR, DM, ME, and CP intake for period 2 was analysed by ANOVA with the fixed effect of treatment, and random effects of cohort nested within block. Overall daily average MR, DM, CP, and ME intake per lamb was analysed by ANOVA with fixed effects of treatment and random effects of block.

2.3 Results

2.3.1 Lamb average daily gain and live weight

A treatment-by-time interaction (P<0.001) was observed such that NM lambs exhibited lower ADG in periods 1 and 3, similar ADG in period 2, and higher ADG in period 4 compared to M lambs (Fig. 2.1). There was also a treatment-by-time effect on lamb live weight (P<0.001) such that in periods 1, 2, and 4, there were no differences between treatments, but at the end of period 3 (week 10), NM lambs were lighter than M lambs (Fig. 2.2).

Figure 2.1 Average daily gain (mean±SEM) of lambs fed meal (M; ■) or no meal (NM; □) over four feeding periods. In period 1 (week 0-3), milk replacer (MR) was provided to both treatment groups and meal offered to M lambs. In period 2 (week 4-5), all lambs were offered unrestricted pasture and MR *ad libitum*, and meal offered *ad libitum* to M lambs. In period 3 (week 6-10), no MR was offered, and M lambs had access to meal *ad libitum*. In period 4 (week 10-12), all lambs had unrestricted access to pasture. There was a significant treatment-by-time interaction (P<0.001). [ab] Values with different superscripts within each period are significantly different (P<0.05).

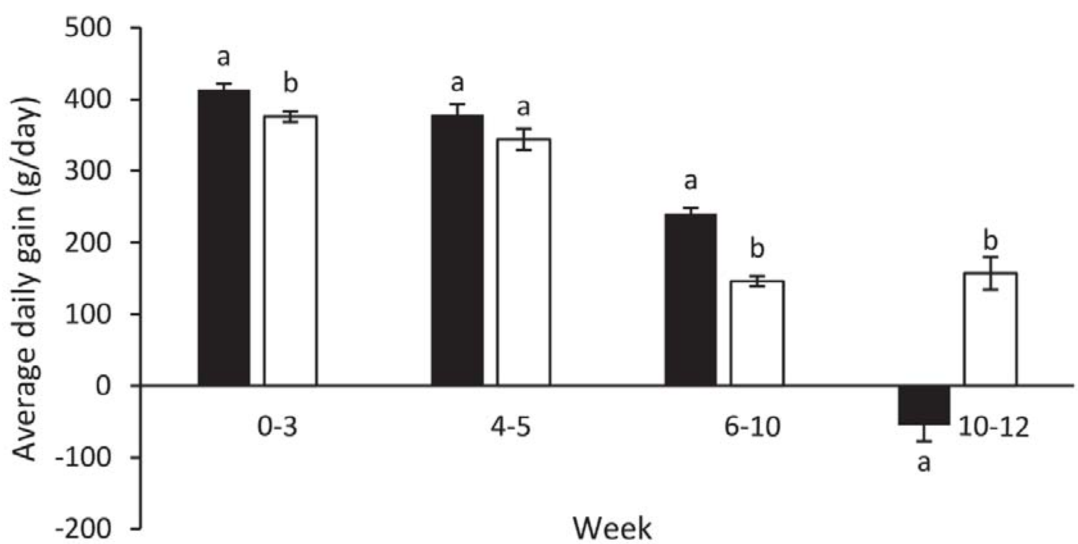
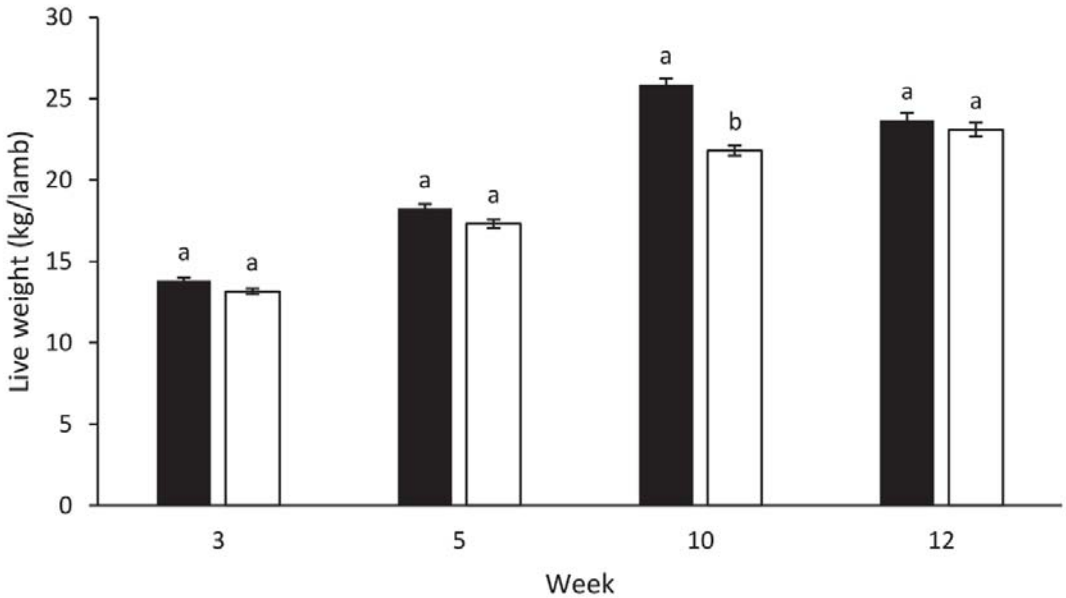


Figure 2.2 Average live weight (mean±SEM) of lambs fed meal (M; ■) or no meal (NM; □) at weeks 3, 5, 10, 12. In period 1 (week 0-3), milk replacer (MR) was provided to both treatment groups and meal offered to M lambs. In period 2 (week 4-5), all lambs were offered unrestricted pasture and MR *ad libitum*, and meal offered to M lambs *ad libitum*. In period 3 (week 6-10), no MR was offered, and M lambs had access to meal *ad libitum*. In period 4 (week 10-12), all lambs had unrestricted access to pasture. There was a significant treatment-by-time interaction (P<0.001). [ab] Values with different superscripts at the end of each period are significantly different (P<0.001).



2.3.2 Intake

There was a treatment effect on MR intake, such that in period 1, NM lambs consumed less MR (P<0.01) than M lambs, but in period 2 there was no difference in MR intake (P>0.05) (Table 2.2). Overall, NM lambs consumed less MR than did M lambs (P<0.05). Due to the exclusion of meal from their diet, NM lambs potentially consumed less DM, ME, and CP from milk and meal sources (P<0.01) in period 2, and over the entire first three periods compared to M lambs (Table 2.2).

Table 2.2 Average daily milk replacer (MR) and meal intake per lamb (mean±SEM) and intake (mean±SEM) of dry matter, metabolisable energy, and crude protein from MR and meal sources for M (fed meal) and NM (not fed meal). In period 1 (P1; week 0-3), MR was provided to both treatment groups and meal offered to M lambs. In period 2 (P2; week 4-5), all lambs were offered unrestricted pasture and MR *ad libitum*, and meal offered to M lambs *ad libitum*. In period 3 (P3; week 6-10), no MR was offered, and M lambs had access to meal *ad libitum*.

P	MR intake (L/day)		Meal intake (g/d)	DMI (g/d)[1]		MEI (MJ/d)[1]		CPI (g/d)[1]	
	M	NM	M	M	NM	M	NM	M	NM
P1	2.37±0.05[a]	2.16±0.05[b]	24	550	478	11.7	10.0	138	122
P2	1.92±0.05[a]	1.76±0.05[a]	104±15	515±15[a]	392±15[b]	10.4±0.3[a]	8.0±0.3[b]	124±4[a]	100±4[b]
P3	-	-	571±15	498±15	-	7.0±0.2	-	85±3	-
1-3	2.03±0.02[a]	1.88±0.02[b]	233±8	520±8[a]	291±8[b]	9.7±0.2[a]	6.3±0.2[b]	116±2[a]	75±2[b]

P=period; DMI=dry matter intake; MEI=metabolisable energy intake; CPI=crude protein intake. [1] Individual meal intakes were not recorded. Average DMI, MEI, CPI were estimated using milk intakes and estimated average meal intakes for each lamb.
[ab] Values within each period with different superscripts are significantly different (P<0.05).

2.4 Discussion

This study aimed to compare growth performance of lambs reared artificially with and without meal during weaning transitions. Feeding meal improved ADG before weaning, however, after meal weaning, M lambs had a growth check. Under our experimental conditions, meal feeding did not appear to benefit the transition to a pasture-only diet.

The lower ADG observed in NM compared to M lambs while indoors (period 1) was likely due to lower overall nutrient intakes, although individual meal intakes were not recorded. This agrees with the results of Poe et al. (1969), who reported that four-week-old lambs (kept with their mothers) that received corn and soy meal had higher ADG than lambs on a solely milk diet. In our study, upon transitioning outdoors (period 2), differences in ADG between groups disappeared, possibly because NM lambs may have consumed more pasture leading to a higher total nutrient intake (milk and pasture) compared to when they had no access to pasture. This may have resulted in ADG similar to M lambs. Additionally, gut fill can range from 6% of live weight in milk fed lambs to 30% in weaned lambs fed forage (National Research Council, 1985). Thus, we speculate there may be an effect of greater gut fill in NM lambs from pasture intake resulting in apparently similar ADG to M lambs. Contrary to our results, Carrasco et al., (2009) found that naturally reared lambs fed meal on pasture had higher ADG compared to that of lambs with no meal provision on pasture. However, in their experiment, there were no transitions between environments, and milk and meal were fed for a longer period (nine weeks) than in our experiment. There are differences in the study by Carrasco et al. (2009) compared to our trial, as ADG was not reported after milk weaning and there was no meal weaning before the end of the experiment. It is likely that the combination of early weaning, transitioning outdoors, and pasture access caused differences in ADG between groups to disappear in our trial.

In the current study, both groups experienced declines in ADG upon the removal of MR (period 3). In calves, meal is considered important around MR weaning, as it allows a higher ADG to be maintained by providing stimulus for rumen development and more nutrients for an easier transition off MR to solid feed (Khan et al., 2016). In agreement with that conclusion, NM lambs had a lower ADG compared to M lambs, which could be due to lower intakes of ME and CP, as their only feed source was pasture, while M lambs on average continued to consume large quantities of meal (500 g DM /lamb/day), likely resulting in greater ME and CP intakes.

Lambs may prefer meal compared to pasture because it is a more energy-dense (De Araújo Camilo et al., 2012) and highly palatable feed (Baumont et al., 2000). Therefore, in our experiment, M lambs may have been substituting meal for pasture in periods 2 and 3, which has been observed in beef calves fed meal (Vendramini et al., 2006), although it is not known if there was substitution, as it was not measured in our trial. After meal weaning (period 4), M lambs experienced a sharp decline in ADG, likely due to a lower nutrient intake compared to that in the previous period. Brown (1964) reported that after early weaning onto pasture, feeding cereal-based meal improved ADG over the entire experimental period compared to that in lambs not offered meal. However, in their trial, lambs consumed less meal than those in our trial (270 *vs.*570 g/d), and were fed meal for a shorter period after weaning (23 *vs.* 31 days). Consequently, the amount of meal offered, or length of time lambs were offered meal, may affect the growth response and pasture intake. It is unclear if the severity of the growth check was due to a rumen or behavioural adaptation period, or a combination of both, after M lambs became reliant on pasture-only to meet their nutrient requirements. In this experiment, feeding meal did not appear to aid the transition to a pasture-only diet, although it is acknowledged that this was a relatively short-term study.

The trial continued beyond the reported timeframes and rumen and metabolic development have been evaluated. The results of these studies will be published elsewhere.

In conclusion, while meal feeding has been previously used to improve ADG when transitioning young ruminants to pasture, in this experiment, the absence of meal feeding did not negatively affect lambs' overall growth to 12 weeks. Including meal in the diet before and after MR weaning improved ADG, however, upon meal removal, there was a large growth check. The results of this study indicate that when lambs are reared on MR *ad libitum* with unrestricted access to good-quality pasture and abruptly weaned, early access to meal may not be required to support growth to 12 weeks of age. Further studies are required to validate the findings of this study.

This chapter has been published, and can be found using the following reference:

Jensen, A. C., Khan, M. A., Knol, F. W., Peterson, S. W., Morel, P. C. H., McKenzie, C., Stevens, D. R., McCoard, S. A. (2017) How does feeding meal affect growth of artificially reared East Friesian-cross dairy lambs? *Proceedings of the New Zealand Society of Animal Production,* 77, 13-17.

Chapter 3: Further investigation into nutrient intake and lamb growth, and estimation of pasture intake

3.1 Introduction

Higher intakes of energy and protein allow greater ADG (Brown et al., 2005), which is often the target in artificial lamb-rearing systems because it allows lambs to be weaned from MR sooner, as well as bred or sold sooner (Litherland and Lambert, 2000, Muir et al., 2000). Energy and protein are important because they are used in forming new tissue and, therefore, are essential for growth, as well as for meeting maintenance requirements (Chambers, 1984, Millward et al., 1976). The data of ADG and intake presented in Chapter 2 were averaged over the dietary and environmental transitions (P1 indoors with MR and meal; P2 outdoors with MR, meal, and pasture; P3 outdoors with meal and pasture; P4 outdoors with pasture), which allowed for a practical interpretation of results and identification of the changes during transitions, however, changes that occurred within each transition period were not presented. It is known that nutrition and growth of lambs are linked (Economides, 1986), and this research will allow greater insight into how differences in nutrient intake and environmental transitions cause differences in lamb growth between the two treatment groups and over the transitions that occurred in this experiment. Lamb growth was averaged and there is little information on individual variation of ADG reported. The reasons for differences in growth between individual lambs may allow insight into the suitability of the systems for all lambs rather than for the 'average' lamb.

Lambs in the rearing system investigated in Chapter 2 were reared for three weeks indoors, and were then continued to be reared on pasture. Feeding regimes during the pre-weaning period can have an effect on the growth rate and adaptation to diets after weaning (Bhatt et al., 2009, Khan et al., 2016), so pasture intake is of interest, but, it was not measured in this experiment. Therefore, an estimation of pasture intake may allow more insight into the reasons for changes in lamb growth that were seen in Chapter 2, particularly after MR and meal weaning, and help in understanding how well lambs transitioned to a pasture diet with and without meal.

The first objective of the current chapter was to further investigate the same experiment in Chapter 2, with a more in-depth investigation of nutrient intakes and growth over the 12-week experimental period in an attempt to better understand what was driving changes in ADG within each weaning transition period between treatment groups and between weeks. The second objective of this chapter was to estimate pasture intake by calculating the theoretical nutrient intake required to meet requirements of maintenance and growth (based on actual growth rates observed) and compare these estimated pasture intakes between treatment groups. The third objective was to describe variation in ADG of lambs that was recorded. It was hypothesised that lambs not fed meal (NM) had greater pasture intakes than those that were fed meal (M) while meal was available, and differences in the growth between treatment groups can be explained by the different amounts consumed and composition of the diets they were fed. In the experiment, MR was measured on an individual and group basis, meal on a group basis and pasture intake was not measured, as there are no practical ways to measure pasture intake in a grazing situation and this was not the focus of the study. The main purpose of the trial was to investigate growth performance between lambs fed or not fed meal and all the requirements for understanding the relationship between intake and performance could not be met. Thus, this chapter attempts to understand these relationships on a theoretical basis.

3.2 Methods

This chapter uses the same animals and data as in chapter 2, therefore, the experimental design and animal and feed measurements remain the same. Information regarding the calculations used in this chapter is provided below.

3.2.1 Calculations

Metabolisable energy (ME) and crude protein (CP) theoretical intakes were calculated using the following formulae to predict the intake that was required to meet the requirements for maintenance and the actual growth of lambs in this study that was measured on a weekly basis.

$$MEmaintenance = a \times (LWTend^{1.75} - LWTstart^{1.75})/1.75/ADG$$

$$MEgrowth = b \times ADG$$

$$MEtheoretical = MEmaintenance + ME\ growth$$

Where a is the ME requirement for maintenance (0.4 MJ/kg $LWT^{0.75}$) and b is the ME requirement for growth (13.8 MJ/kg LWT gain), reported for lambs by Danso et al. (2016). LWTend = live weight at the end of the week and LWTstart= live weight at the beginning of the week.

$$CPmaintenance = c \times (LWTend^{1.75} - LWTstart^{1.75})/1.75/ADG$$

$$CPgrowth = d \times ADG$$

$$CPtheoretical = CPmaintenance + CPgrowth$$

Where c is the CP requirement for maintenance (2.74 g CP/kg $LWT^{0.75}$) and d is the CP requirement for growth (0.23 g CP/ 1 g ADG), reported for lambs by Danso et al. (2016).

Estimated pasture intake on a weekly basis was calculated as the difference between the actual ME and theoretical ME intakes multiplied by the ME composition of pasture. This gives an estimate of what pasture intake was required to meet the ME requirement for maintenance and growth in that week (Macoon et al., 2002). A similar formula was followed for calculating pasture intake using CP on a weekly basis. Composition of pasture used in calculations in reported in Table 3.2.

3.2.2 Statistical analysis

Two statistical packages were used due to each software having different functionality. A repeated-measure mixed-effects model (REML) was fitted for ADG with fixed effects of birth rank, week, and treatment group, and random effects of lamb nested in pen within block, with initial live weight fitted as a covariate. Theoretical intakes and estimated pasture intakes were analysed using REML with fixed effects of week and treatment and random effects of cohort nested in block. These statistical analyses were conducted in R (R Core Team 2016).

GenStat 18th edition (VSN International 2015) was used for all the following analyses. MR intake for weeks one to three was analysed using REML, with fixed effects of birth rank and treatment group and initial live weight used as a covariate. The data were log transformed to meet the assumptions of normality and homogeneity of variance. MR intake for weeks four and five, and ME and CP intake were analysed by analysis of variance (ANOVA) with fixed effects of week and treatment group, and random effects of cohort nested in block. A different model for week four and five compared to weeks one to three was used due to the change in intake measurement from an individual basis to a group basis.

3.3 Results

3.3.1 Average daily gain

A treatment-by-time interaction ($P<0.001$) was observed such that NM lambs exhibited lower ADG in weeks three, six, seven, and eight, similar ADG in weeks one, two, four, five, and nine, and higher ADG in weeks ten, eleven, and twelve compared to M lambs (Figure 3.1). There were differences in ADG between weeks across the trial (Figure 3.1). Both groups had similar ADG in weeks one and two, but in week three M lambs ADG was higher than week two, but ADG remained unchanged in the NM group. In week four, both groups exhibited declines in ADG compared to the previous week, which was associated with the transition from indoors to outdoors. But in week five, there was an increase in ADG for both M and NM lambs and ADG reached the same value as M lambs had previously achieved in week three. After MR weaning (week six), both groups had lower ADG, but NM lambs was lower than M lambs and increased to week seven and again to week eight, while M lambs' ADG in week six and seven remained constant. In week eight, M lambs had a higher ADG than week seven, that was the same as had been achieved in week three and five, and then decreased to a constant ADG in weeks nine and ten. NM lambs experienced some fluctuations in ADG from week eight to 12. From week ten, M lambs ADG declined each week while NM lambs ADG declined between week ten and 11, and was then constant between week 11 and 12.

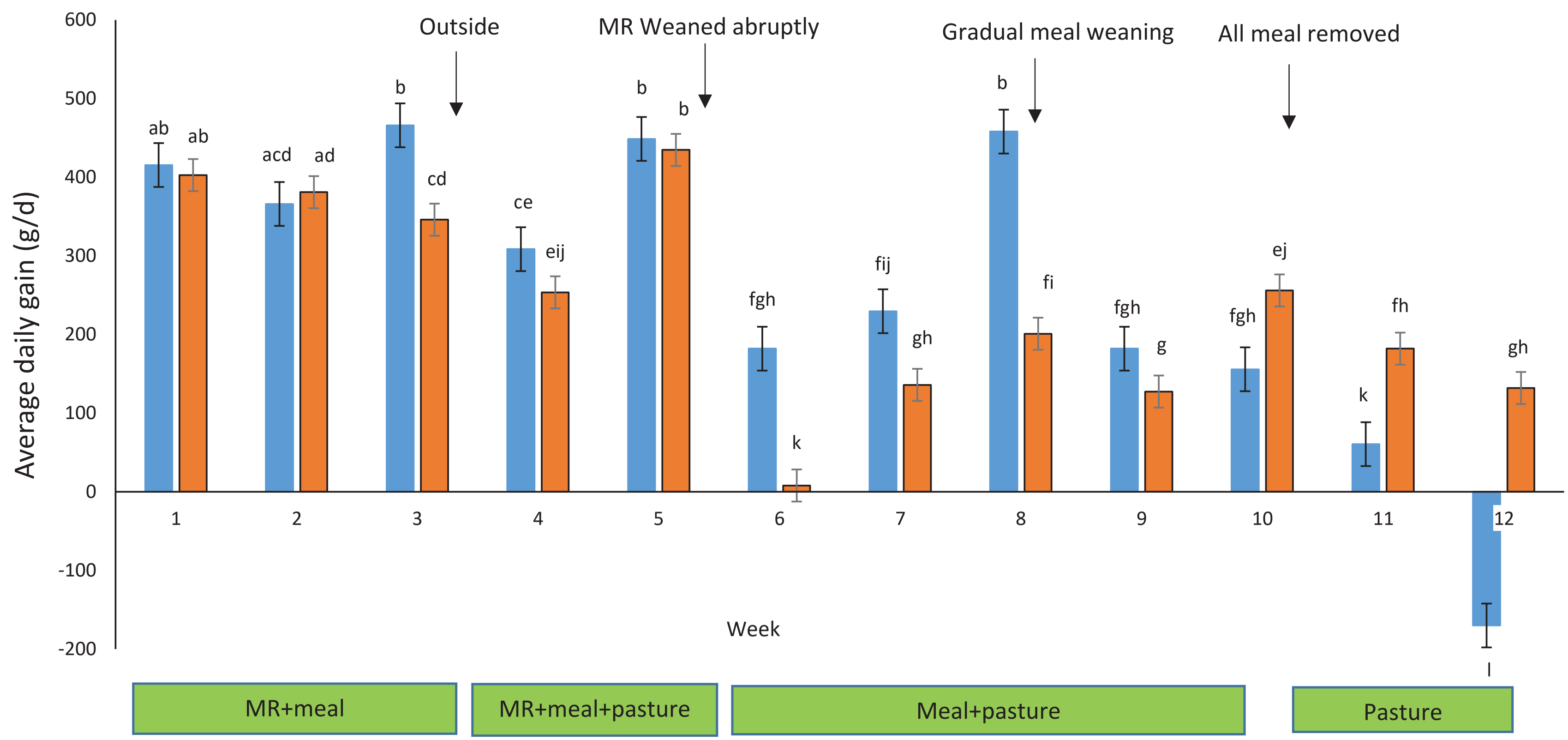


Figure 3.1. Weekly average daily gain (mean±SEM) of lambs fed meal (M;) or no meal (NM;). In weeks one to three, lambs were indoors and milk replacer (MR) was provided to all and M lambs were fed meal in addition to MR. In weeks four and five, lambs were outdoors grazing unrestricted pasture and continued to receive MR *ad libitum* and M lambs were still offered meal *ad libitum.* From week six to ten, no MR was fed, but M lambs had continued access to meal *ad libitum,* until it was gradually weaned over ten days in weeks nine and ten. From halfway through week ten to week 12, lambs' only source of feed was pasture. There was a significant treatment-by-time interaction ($P<0.001$). [ab] Values with different superscripts are significantly different both within and between treatment groups over time ($P<0.001$).

Figure 3.2 is a summary of the distribution of lamb ADG for M and NM lambs each week that shows the maximum and minimum ADGs, and any outliers. The median, lower quartile, upper quartile, and interquartile range are also represented. Points are considered outliers if they are more than 1.5 times the interquartile range from the upper or lower quartile.

In the first three weeks, there were no large differences between the ADG ranges of the two treatment groups. After MR weaning, in week six, the distribution of ADG of NM lambs was moderately even compared to that in the M lambs (Range= 571 *vs.* 642). The M group also had more outliers both above and below the main ADG distribution compared to NM lambs (4 *vs.* 1). In weeks eight and nine, there continued to be one outlier that had a lost weight, but this was not the same lamb each week. In week nine, the interquartile range of M lambs ADG decreased compared to the previous week, and there were also outliers in the M group that continued to have a high ADG compared to NM lambs. In the same week, NM lambs showed a similar pattern of distribution compared to the previous week, with a slight decrease in ADGs recorded. In week ten, there was little change in distribution of ADG compared to that in week nine. In week 11, the interquartile range of M lambs started to increase. Finally, by week 12, the largest range (-857-214 g/d) and interquartile range (-410-71 g/d) of lamb ADG over the entire experiment was recorded in the M lambs. In week 12, 37% of lambs in the M group maintained a positive ADG, while others were losing weight (63%), and only 10% of NM lambs were losing weight during that week.

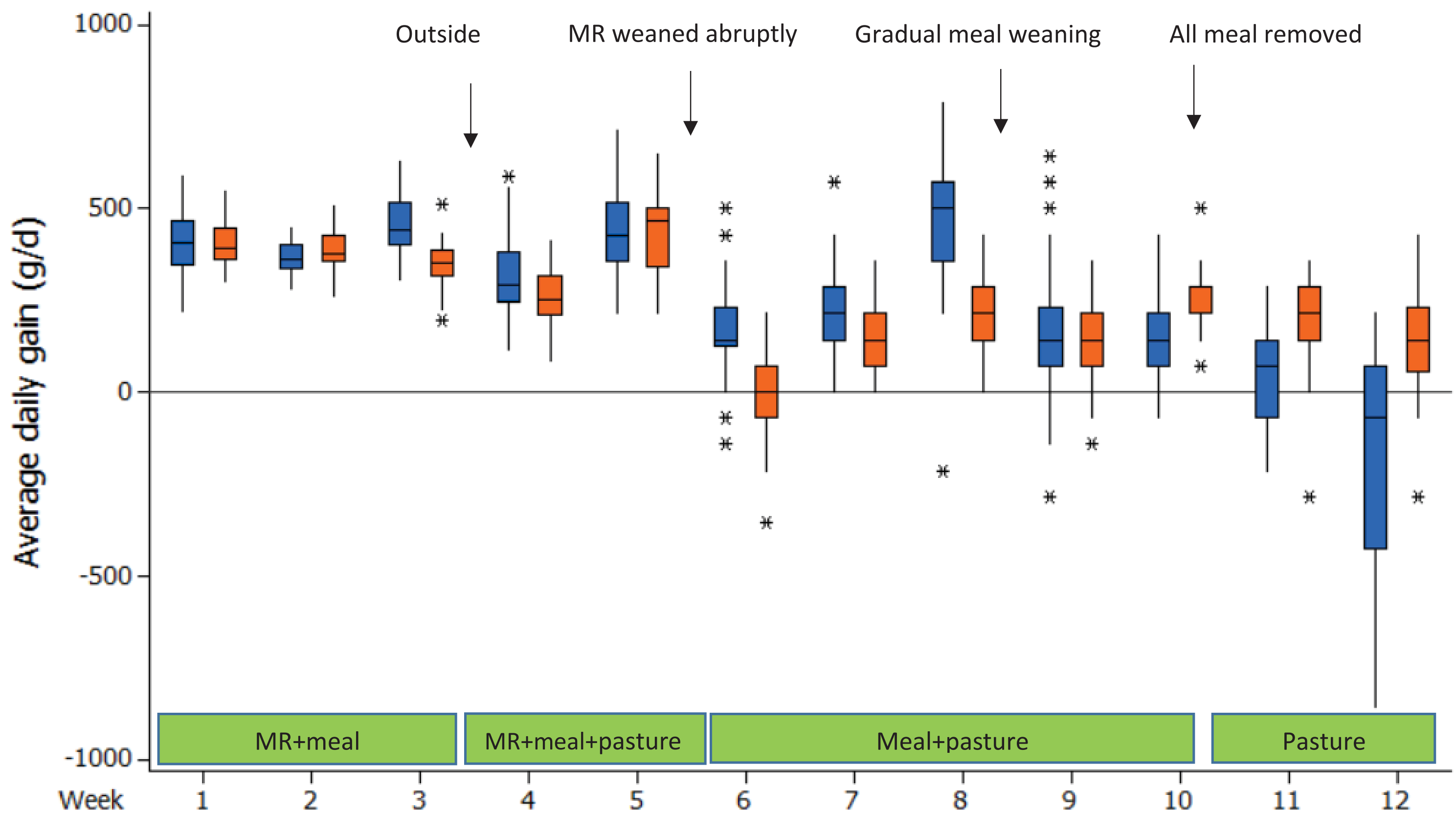


Figure 3.2. Box and whisker diagram showing variation in average daily gain (ADG) of lambs fed meal (M; ■) or no meal (NM; ■). In weeks one to three, lambs were indoors and milk replacer (MR) was provided and M lambs were fed meal in addition to MR. In weeks four and five, lambs were outdoors grazing unrestricted pasture and continued to receive MR *ad libitum* and M lambs were still offered meal *ad libitum.* From week six to ten, no MR was fed, but M lambs had continued access to meal *ad libitum,* until it was gradually weaned over ten days in weeks nine and ten. From halfway through week ten to week 12, lambs' only source of feed was pasture. Whiskers represent the top and bottom 25% of observations and the box represents the interquartile range (IQR) and middle 50% of observations, with the line within the box representing the median. * represents outliers (more than 1.5 times the IQR from the upper and lower quartile.

3.3.2 Milk replacer and meal intake

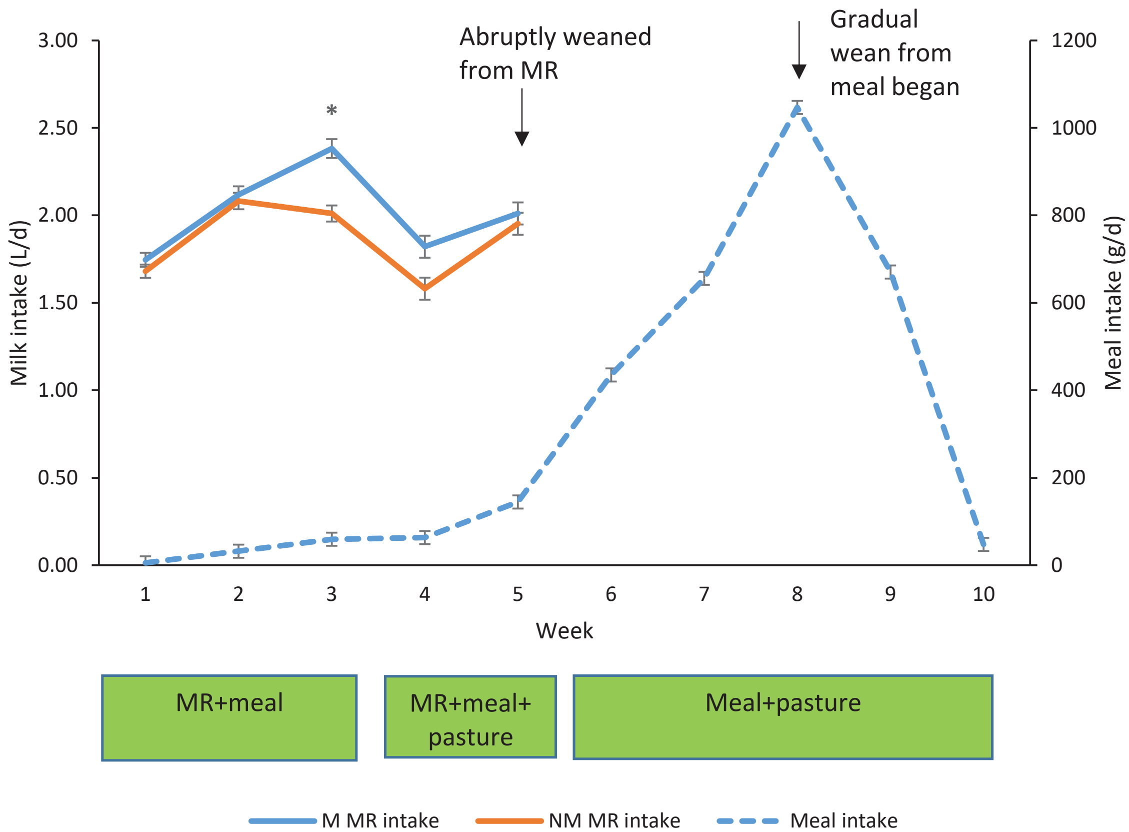


Figure 3.3. Average daily milk replacer (MR) intake (mean±SEM) for M (dotted line) and NM lambs (solid line) and meal intake (mean±SEM) for M lambs (dashed line) on secondary axis. In weeks one to three, lambs were housed indoors and fed MR *ad libitum.* In weeks four and five, lambs were kept on unrestricted pasture and continued to have access to MR *ad libitum*. Lambs were abruptly weaned from MR at the end of week five. Until week eight, meal was fed to M lambs *ad libitum*, and was then gradually weaned over ten days in weeks nine and ten. * indicates a significant difference (P<0.001) between treatment groups.

The average weekly intake of MR and meal per lamb is shown in Figure 3.3. Milk replacer intake was compared between treatment groups and there was a significant time-by-treatment interaction (P<0.001), such that in weeks one and two, there was no difference in MR intake between M and NM lambs, but in week three, NM lambs were consuming less than M lambs. In weeks four and five, there was no effect of treatment on MR intake (P>0.05), but MR intake increased from week four to five (P<0.05).

3.3.3 Nutrient intakes

To gain a greater understanding of the relationship between growth and nutrient intakes in this study, the theoretical intakes of ME and CP required to meet the observed growth rates were calculated. These are shown in Table 3.1. These theoretical intakes were used to estimate pasture intake according to the equations outlined in the methods section.

No statistical analysis of actual intakes was conducted in weeks one to three because there was only one measurement of meal intake per day for the whole group. However, meal intake numerically increased across the first three weeks. In both weeks four and five, M lambs consumed more ME and CP than did NM lambs ($P<0.05$), and their intakes increased from week four to five (Figure 3.4a).

Table 3.1. Average weekly theoretical metabolisable energy intake (MEI) and theoretical crude protein intake (CPI) for M (fed meal) and NM (not fed meal) lambs to achieve the observed growth rates. Feeding regime of milk replacer (MR), meal, and pasture is shown in the table for M lambs, and NM lambs received the same treatment except that meal was excluded. All diets were provided *ad libitum*.

		Theoretical MEI (MJ/d)[1]		Significance	Theoretical CPI (g/d)[2]		Significance
Feeding regime	**Week**	M	NM		M	NM	
M: MR + meal; NM; MR	**1**	7.2	7.0	NS	105	103	NS
	2	7.0	7.2	NS	97	101	NS
	3	8.9	7.2	*	124	97	*
M: MR + meal + pasture; NM: MR +pasture	**4**	7.1	6.3	NS	91	78	NS
	5	9.5	9.2	NS	126	122	NS
M: Meal + pasture; NM: Pasture	**6**	6.1	3.5	*	67	25	*
	7	7.0	5.4	*	79	56	*
	8	10.5	6.4	*	134	71	*
	9	7.0	5.6	*	72	56	NS
	10	6.8	7.5	NS	67	87	NS
M and NM:Pasture	**11**	5.5	6.7	NS	46	71	*
	12	2.3	6.2	*	-7	61	*
	SEM	0.4	0.5		6	8	

*indicates there is a significant difference ($P<0.0001$) between treatment groups within a row [1]Theoretical ME= MEmaintenance + ME growth, where: MEmaintenance = a x ($LWTend^{1.75}$ – $LWTstart^{1.75}$)/1.75/ADG, and MEgrowth = b x ADG. [2]CPtheoretical = CPmaintenance + CPgrowth, where CPmaintenance = c x ($LWTend^{1.75}$ - $LWTstart^{1.75}$)/1.75/ADG, and CPgrowth = d x ADG. a= 0.4 MJ/kg $LWT^{0.75}$, b=13.8 MJ/kg LWT gain, c=2.74g CP/kg $LWT^{0.75}$, and d=0.23 g CP/ 1 g ADG (Danso et al., 2016).

A major aim of this chapter was to estimate pasture intakes and find if there were differences in estimated intakes between groups. There was a treatment-by-time interaction (P<0.0001) for the pasture intake, such that no pasture needed to be consumed in week four or five to meet calculated ME requirements for either treatment group, but in weeks six, seven, eight, nine and twelve, NM lambs needed to consume more pasture compared to M lambs to meet their calculated requirements (Figure 3.4b). In weeks seven, eight, and nine, it was estimated that M lambs did not need consume any pasture to meet their calculated requirements, while NM lambs did. In weeks ten and eleven, NM and M lambs had a similar estimated pasture intake to meet their nutrient requirement for ME for maintenance and observed growth (Figure 3.4b).

There was a treatment-by-time interaction (P<0.0001) for the estimated pasture intake required to meet CP requirements for maintenance and observed growth. In weeks four, five, seven, eight, nine, and twelve, M lambs did not need to consume any pasture to meet their calculated requirements (Figure 3.4b). In weeks five, six, ten and eleven, NM lambs needed to consume the same amount of pasture as M lambs to meet their CP requirements, and in weeks seven, eight, nine, and twelve, it was estimated that NM lambs needed to consume more pasture than M lambs to meet their CP requirements for maintenance and the growth that was recorded (Figure 3.4b). Data used in estimating pasture intake is shown in Table 3.2.

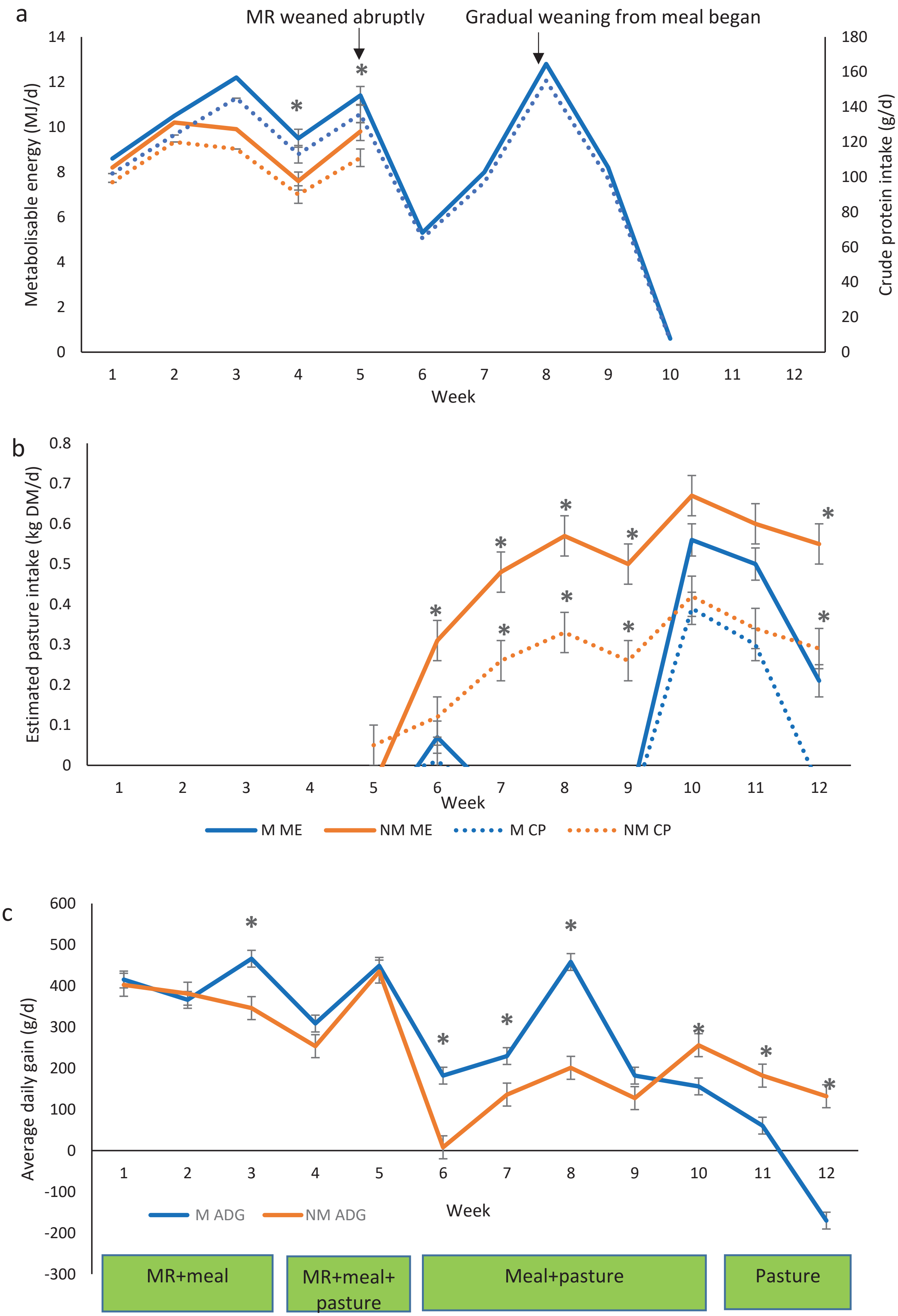

a
MR weaned abruptly
Gradual weaning from meal began
Metabolisable energy (MJ/d)
Crude protein intake (g/d)
Week
b
Estimated pasture intake (kg DM/d)
Week
M ME
NM ME
M CP
NM CP
c
Average daily gain (g/d)
M ADG
NM ADG
Week
MR+meal
MR+meal+ pasture
Meal+pasture
Pasture

Figure 3.4. (a) Metabolisable energy (ME; solid line) and crude protein (CP; dotted line) intake (mean±SEM) from milk replacer (MR) and meal sources for M (blue) and NM lambs (orange). (b) Weekly estimated pasture intake (mean±SEM) that was required to meet ME[1] (Solid line) and CP[2] (dotted line) calculated maintenance requirements and requirements for the growth recorded for M (blue) and NM (orange) lambs. (c) Average daily gain (mean±SEM) of M (blue) and NM (orange) lambs. In weeks one to three lambs were indoors and fed MR and meal ad libitum, they were moved outdoors in week four, and MR and meal continued to be fed. Lambs were abruptly weaned from MR at the end of week five. Meal continued to be fed until week eight, when it was gradually weaned over ten days, so that all meal was removed part-way through week ten. NM lambs received same treatment except meal was excluded. [1]Estimated pasture DMI for ME=Theoretical MEI – actual MEI x pasture ME composition. [2]Estimated pasture DMI for ME=Theoretical CPI – actual CPI x pasture CP composition. * indicates a significant difference between treatment groups (P<0.05).

Table 3.2. Actual metabolisable energy (ME) and crude protein (CP) concentrations of pasture used to estimate the amount of pasture that was required to meet ME and CP requirements for maintenance and growth of lambs.

Nutritive component	Treatment	Week 4	Week 5	Weeks 6-9	Weeks 10-12
ME	M	12.2	12	11.0	11.2
(MJ/kg DM)	NM	11.6	11.7	11.1	11.3
CP (%DM)	M	26.9	25.2	21.5	15.5
	NM	24.7	22.5	21.6	20.6

M= meal group; NM= no meal group. Composition was determined by NIR analysis (Nutrition Laboratory, Massey University, Palmerston North, New Zealand).

Tables 3.3 and 3.4 show the contribution of each feed component to overall intake (including calculated pasture intake values). It can be seen from calculated pasture values, only a small amount of pasture would need to have been consumed to meet CP requirements, but none needed to be consumed to meet ME requirements for NM lambs before weaning. Meal lambs' contribution of meal to ME and CP intake increased from weeks one to seven, when it formed 100% of the diet according to the calculated requirements. As gradual weaning from meal occurred, M lambs were estimated to increase pasture intake, as pasture gradually became M lambs only feed source.

Table 3.3. The contribution (%) of each feed source to total metabolisable energy (ME) intake for M (fed meal) and NM (not fed meal) lambs. Milk replacer (MR) and meal intakes are actual intakes, while pasture is calculated as the amount that was theoretically required to be consumed to meet lambs' calculated growth and maintenance requirements.

		M			NM		
Feeding regime	Week	MR	Meal	Pasture	MR	Meal	Pasture
M: MR + meal; NM: MR	1	99	1	0	100	0	0
	2	97	3	0	100	0	0
	3	95	5	0	100	0	0
M: MR + meal + pasture; NM:MR + pasture	4	92	8	0	100	0	0
	5	85	15	0	100	0	0
M: Meal + pasture; NM: pasture	6	0	87	13	0	0	100
	7	0	100	0	0	0	100
	8	0	100	0	0	0	100
	9	0	100	0	0	0	100
	10	0	9	91	0	0	100
M and NM: Pasture	11	0	0	100	0	0	100
	12	0	0	100	0	0	100

Table 3.4. The contribution (%) of each feed source to total crude protein (CP) intake for M (fed meal) and NM (not fed meal) lambs. Milk replacer (MR) and meal intakes are actual intakes, while pasture is calculated as the amount that was theoretically required to be consumed to meet lambs' calculated growth and maintenance requirements.

		M			NM		
Feeding regime	Week	MR	Meal	Pasture	MR	meal	Pasture
M: MR + meal; NM: MR	1	99	1	0	100	0	0
	2	97	3	0	100	0	0
	3	95	5	0	100	0	0
M: MR + meal + pasture; NM:MR + pasture	4	92	8	0	100	0	0
	5	84	16	0	91	0	9
M: Meal + pasture; NM: pasture	6	0	97	3	0	0	100
	7	0	100	0	0	0	100
	8	0	100	0	0	0	100
	9	0	100	0	0	0	100
	10	0	10	90	0	0	100
M and NM: Pasture	11	0	0	100	0	0	100
	12	0	0	100	0	0	100

3.4 Discussion

This chapter aimed to further investigate nutrient and estimated pasture intakes and growth of lambs reared artificially when fed or not fed meal, to further understand the findings reported in chapter 2. This was done to find the growth changes that occurred within each transition period and look at the reasons for differences in growth in order to understand relationships between growth and nutrient intake from different feed sources. Additionally, since pasture intakes were not measured, an indication of consumption was calculated in this chapter to aid in the investigation of growth and its relation to nutrient intake.

3.4.1 Average daily gain and nutrient intake

In the first two weeks, there were no differences in growth between treatments, but by the third week, M lambs were growing faster than NM lambs. This coincided with a numerically higher intake of ME and CP resulting from the higher MR intake and the intake of meal. It is unclear why M lambs had a higher intake of MR in week three (Figure 3.3), although they were slowly increasing their meal intake over the three-week indoor period, and it is possible that increased meal consumption stimulated thirst. There is a positive correlation between water intake and solid feed intake (De Passillé et al., 2011), and so it is speculated that M lambs drank more MR, despite water being freely available, to meet some of their increased water requirements. It has previously been reported that lambs that had access to MR *ad libitum* plus creep feed (composed of wheat, alfalfa hay, and canola meal) in early life (birth to three weeks old) had lower ADG, compared to those that had access to MR alone, which was hypothesised to be due to a high consumption of creep feed prior to any rumen development (Mir et al., 1987). A slightly lower MR intake in lambs fed creep compared to those fed just MR (410 *vs.* 390 g/d MR powder) in the experiment by Mir et al. (1987) may account for some of the lower growth observed in lambs fed creep. This contrasts with the findings in the current trial. Differences between the composition of the solid feeds between Mir et al. (1987) and the current trial may account for some differences that were seen in growth. Lambs in the trial by Mir et al. (1987) were fed alfalfa hay, in addition to rolled wheat and canola meal, contrary to our trial where no bulky fibre sources were provided in the first three weeks, thus, in the trial by Mir et al. (1987), hay may have provided bulk and gut fill, which can depress voluntary feed intake (Woods, 2004).

Upon moving outdoors, the ADG of both groups declined and there was little evidence of a difference in ADG between treatment groups. While the reasons for this decline are not exactly known, there were several changes that occurred that week which may have affected intakes and growth. The type of milk feeding apparatus changed from an automatic feeder to a bucket feeder with different teats, which would have required a period of adaption to the new system of MR feeding. The MR intake for this week numerically decreased compared to the previous week, so it is possible the change in feeder reduced MR consumption. There was also a change of environment, as they moved from an indoor temperature-controlled facility to a cooler outdoor environment with no slow transition period, which may have increased requirements for thermogenesis (CSIRO, 1990), resulting in less nutrients available for growth. Napolitano et al. (2008) reported that there may be significant stress associated with a change of feeder type and environment, both of which occurred on the same day in our trial, thus, these factors may have lowered intakes of MR, and subsequent ADG. However, after one week outdoors, ADG of both groups increased, therefore, whatever the cause of the lower growth rate in week four, the effects were short-term.

In week five, both groups were able to reach the same ADG that was occurring in M lambs in week three. From calculated pasture intakes, NM lambs were consuming only a small amount of pasture (9% of total CP intake), and M lambs were only consuming small amounts of meal (16% of total CP intake) and no estimated pasture intake. Thus, this increase in the growth rate seen between weeks four and five is most likely not largely due to solid feed intake, irrespective of whether they were allowed meal and pasture or just pasture. The increase in growth rate from week four to five in both groups was likely due to increasing MR intake, although this increase in MR intake is not significant, there is an apparent numerical increase and the lack of significance may be due to a small sample size. The increasing MR intake between weeks four and five mirrors the increasing ADG between these weeks, so it is likely that the higher MR intake, and therefore, nutrient intake, can explain why the ADG increased in week five. The sample size for MR intakes significantly decreased between weeks three and four (30 measures of MR intake per day per treatment (individual basis) to three measures of MR per day per treatment (cohort basis)), which may explain why no significant differences were seen in MR intake in and between week four and five. It is also possible there is a greater effect of gut fill as lambs consume more pasture, which may affect weight measurements (discussed in Chapter 2).

The abrupt wean from MR caused a large growth check, which has been previously reported in lambs (Bimczok et al., 2005, Heaney et al., 1984) and calves (Khan et al., 2011, Sweeney et al., 2010). Lambs in the M group had a growth check when weaned from MR, likely due to a loss in nutrient intake, but, the meal allowed lambs to undergo a smaller growth check compared to the NM lambs (ADG decreased from 447±28 to 181±28 g/d for M and from 435±20 to 9±20 g/d for NM between week five and six). The lower growth check in M lambs likely occurred because they were allowed access to a more energy-dense feed (meal) than pasture that allowed a greater nutrient intake to be maintained compared to the previous week when MR was available in addition to pasture (De Araújo Camilo et al., 2012). Milk replacer is very nutrient dense and has a high digestibility (Bhatt et al., 2009), which supports faster growth on a diet that is mainly MR, compared to their post-weaning diet.

However, ADG of NM lambs then increased for the next two weeks (six to seven and seven to eight) (average LWT in week seven:18.2 kg, average LWT in week eight:19.6), which was likely due to rumen development, allowing greater utilisation of the diet (Khan et al., 2016), and greater pasture consumption resulting in a greater nutrient intake and, thus, more nutrients available for growth. Meal consumption lowered the amount of time devoted to grazing in beef calves, which may have lowered maintenance requirements (Vendramini et al., 2006). Similarly, in our experiment, M lambs were observed to spend less time grazing than those in the NM group, when both meal and pasture were available in week 7 (Nieper et al., 2017). Maintenance requirements may be lower in animals fed grains compared to pasture due to reduced time spent eating, reduced walking/grazing, and a lower cost of chewing and rumination (Osuji, 1974, Suzuki et al., 2008). This may have occurred in the current experiment, allowing higher ADG in M lambs because it is possible more energy could have been partitioned for growth, compared to NM lambs. The different nature of the two diets (glucogenic *vs.* lipogenic) may result in different tissue deposition, as discussed below. The increase in meal consumption may have caused an increase in gut fill, which contributed to the apparent increase in ADG, so the higher ADG may not be entirely true bodyweight gain. There was no significant increase in ADG for M lambs between week six and seven, despite a large increase in meal intake. There was a numerical increase in ADG of M lambs between weeks six and seven, but, the increase in meal intake between these weeks should have resulted in a greater increase in ADG than was recorded. This may indicate that M lambs (19.5-21.1 kg, average LWT in week six and seven) were also undergoing rumen development, so may not have been able to fully utilise all the nutrients available. Additionally, other parts of the gastrointestinal tract or metabolic system may have prevented lambs utilising all the nutrients that they consumed.

Grain-based glucogenic diets result in large production of propionate, glucogenic amino acids, and lactic acid, while pasture-based lipogenic diets result in production of acetate and butyrate (Van Knegsel et al., 2007). There is a lack of data in lambs regarding the transition from a glucogenic to a lipogenic diet. The lipogenic diet increases the precursors for lipogenesis compared to a glucogenic diet (Van Knegsel et al., 2007). However, in lactating cows, glucogenic diets improve energy balance and reduce fat mobilisation (Van Knegsel et al., 2007) and may also allow more amino acids to be used for tissue growth compared to lipogenic diets (Schroeder and Titgemeyer, 2008), which may allow greater ADG when consuming a grain-based diet.

In week eight, M lambs did not require any pasture to meet the requirements for growth, while NM lambs could only eat pasture, which was the likely cause of the lower ADG seen in NM lambs, as pasture is less energy dense than meal. However, M lambs were observed to be consuming pasture in week seven (so were likely still consuming pasture in week eight), although they did spend less time grazing than did NM lambs (Nieper et al., 2017). However, from week seven to nine, M lambs did not require any consumption of pasture according to the calculated growth and maintenance requirements. It has been found that sheep will consume fibrous feeds even when energy-dense meal is available (Baumont et al., 2000). Thus, it is possible there was some pasture consumption by M lambs (as seen through visual observations), despite there being no necessity to do so, in terms of theoretical intakes and requirements and, therefore, pasture intake was estimated to be zero, but, the actual consumption of pasture is not known, as it was not measured. However, visual observations of grazing recorded in weeks five, seven, ten, and twelve (Nieper et al., 2017) allow an indication that pasture intake was occurring despite what was calculated. Lambs in the M group were observed to spend less time grazing (as a percentage of time during the observation period) in weeks five (32% *vs.* 36%), seven (39% *vs.* 72%), and twelve (60% *vs.* 72%) than did NM lambs (Nieper et al., 2017), and the shorter amount of time spent grazing in weeks five and seven in the M group is likely because they also had meal available to eat.

As indicated from the visual observations, there may be differences in what lambs actually required (and consumed) and what was calculated, as requirements can vary with diet, breed, the environment, management, activity, sex, and age (Cannas et al., 2004, Galvani et al., 2008), and these factors differed between the current trial and that of Danso et al. (2016) on which the calculations are based. These differences may introduce inaccuracy into the calculated requirements, and may partly explain why visual observations of grazing did not match with the calculated requirement of pasture consumption (as lambs were observed to spend time grazing when the estimated pasture intake was zero). There are other data available on lamb requirements, but all differed in these aspects compared to the current trial. Lamb growth will be affected by the digestibility, absorption, and efficiency of nutrient utilisation (Waghorn and Clark, 2004). Thus, it is possible that the consumption of pasture was greater than that calculated, (and this was observed through grazing observations) because not all the CP and ME from pasture ingested would have been digested, absorbed, and utilised, particularly until the rumen develops (Cruickshank, 1986).

The ADG differences between M and NM lambs that occur in weeks six, seven, and eight may be due to differences in organic matter digestibility (OMD) between the diets. Pasture OMD was lower than that of meal (~80% *vs.* 92% DM), which would have allowed faster and more complete digestion of the meal diet, and it has been previously reported that pasture has a lower efficiency of ME utilisation compared to grain-based meal (when fed to dairy cows) (Annison et al., 2002, Waghorn and Clark, 2004). The efficiency of utilisation of ME for growth (K_g) is usually between 20 and 50% in ruminants (Rattray and Joyce, 1976). For lambs on a high-quality diet, such as meal, the K_g can be above 50% and on a pasture diet was found to be 29% (Fennessy et al., 1972). Thus, these dietary differences were likely responsible for the differences in ADG between M and NM lambs. But, by the time all meal was removed and both groups were reliant on pasture, in week 11, ADG of M lambs was lower than that of NM lambs, and the following week it was lower still, which may be related to the transition between meal and pasture.

Due to the greater energy density of meal compared to pasture (Baumont et al., 2000), NM lambs would have to graze for a much longer period to obtain the same amount of ME and CP as lambs that were consuming meal. Lambs in the NM group were observed to be grazing for a greater percentage of time in week seven than were M lambs (72% *vs.* 39%) (Nieper et al., 2017), but were unable to achieve the same growth rate as M lambs in this week, likely because they could not consume the same amount of ME and CP as did M lambs, despite the longer grazing time. In addition, these two feed sources are fermented differently (Van Knegsel et al., 2007), which can alter tissue deposition, such that more amino acids may be available for muscle growth (Schroeder and Titgemeyer, 2008) in the M lambs because they are fed meal (glucogenic *vs.* lipogenic, discussed above). There may also be substitution of meal for pasture (Vendramini et al., 2006), as described in chapter 2.

The increase in time spent grazing in week ten in M lambs occurred when all meal was removed, so was probably lambs attempting to compensate for the loss of meal and maintain their nutrient intake. However, M lambs had a lower ADG than NM lambs, despite spending the same amount of time grazing in this week, which is likely due to the requirement for an adaptation period to a solely pasture diet (discussed below).

In week twelve, as M lambs lost weight, the amount of pasture that they needed to consume to meet calculated growth requirements decreased, and was lower than that of NM lambs. In addition to the estimated requirements for pasture decreasing, M lambs were also observed to spend less time grazing than did NM lambs in week 12 (Nieper et al., 2017). There are suggestions that high meal intakes combined with low roughage intake can reduce the rate of rumen development (Suárez et al., 2007) and negatively impact ruminal health (Castells et al., 2013), and it may be that these factors were affecting pasture intakes or utilisation of the pasture diet in M lambs, as the rumen may require time to adapt to the new diet.

There may also be fewer cellulolytic bacteria in the rumen (as seen in calves) (Beharka et al., 1998), which may slow the utilisation of pasture and transition from a mainly meal to a solely pasture diet that occurred in the M group. The ten-day gradual-weaning period was supposed to allow an easier transition off meal (Khan et al., 2016, Manso et al., 1996), and while it may do this compared to being abruptly weaned from meal, a longer transition period may have lowered the subsequent growth check that was seen because it would have allowed more time for the rumen to adapt to the pasture diet. However, these effects would be expected to occur closer to the time of removal of meal, rather than in week twelve, when lambs had not consumed any meal for sixteen days. Average daily gain may decline in week 12 due to the fact live weight loss would not occur instantly. It is also possible that as M lambs appear to increase their pasture consumption in week ten, when meal is removed (Nieper et al., 2017), there was more gut fill in this week, so the loss of live weight is not seen. In subsequent weeks, there was likely little change in the amount of gut fill, which allowed the changes in lamb live weight not due to gut fill to be observed.

In weeks ten to twelve, the CP content of M lambs' pasture declined from the value recorded in the previous weeks (21.5% to 15.5% DM), while the CP content of the pasture NM lambs were fed did not. This was only a pool of samples, so further analysis of pasture nutritive content for each cohort per week may be required. The CP content of M lambs' pasture was below the optimal level that is required for young livestock of 19% or greater CP content (Waghorn and Clark, 2004). Thus, it is possible that this poor CP content of pasture may have restricted lamb growth over this period, although not to the extent of low growth that was observed and since lambs were estimated to be consuming very little pasture, it is likely to have occurred in combination with the other factors discussed, such as poor rumen health, and the time required for the adapting rumen microbe population. This decline in CP content of pasture may have occurred because M lambs were consuming less pasture, thus, allowing a decline in pasture quality. However, why ME content of pasture did also not decrease is unclear.

Voluntary feed intake (VFI) of pasture-fed lambs is reported to range between 0.51 to 1.23 kg DM/d for a 20 kg lamb, depending on mature live weight and digestibility of the pasture (CSIRO, 1990). In the current experiment, the estimated intakes of DM were at the lower end of this range, however, for most of the experiment lambs weighed less than 20 kg. It is also possible that lambs consumed more pasture than was required to meet their calculated

CP and ME requirements. The calculations assume that lambs will be able to utilise all the ME and CP that is consumed in order to meet their requirements for maintenance and growth and assumes all ME and CP to be equal despite the different sources, however, this may not be the case (Annison et al., 2002).

3.4.2 Individual variation in average daily gain

Individual variation in ADG is not usually reported in studies, but it did provide some interesting findings. The reasons for differences in ADG among lambs cannot be determined, however, there are several possibilities. The lambs used in this trial were all East-Friesian cross lambs, but, the other breed involved in the cross varied between lambs and its genetic contribution was unknown. Therefore, there may be some differences in growth rate between individuals due to breed and the different birth weights, which can affect subsequent growth rates (Greenwood et al., 1998, Shrestha et al., 1982). Some of the variation is also likely due to random effects, such as gut fill at the time of weighing over the course of the trial. Gut fill ranges from 6% in milk fed lambs to 30% of live weight in lambs consuming pasture (National Research Council, 1985), and can vary with the time after a feed that weighing is conducted. It is also possible that ADG was affected by intakes. Some lambs did not undergo large growth checks with weaning, from both MR and meal, compared to others. It is possible there were differences among individuals in intake of MR, meal, and pasture. A higher solid feed intake prior to weaning may have allowed more rumen development compared to a lamb that consumed mainly MR (Baldwin et al., 2004), and therefore, could have allowed an easier transition, in terms of growth, to a diet that relied on the rumen (week six) (Khan et al., 2016). Despite these factors possibly affecting

ADG, the variation was fairly consistent across most weeks, with the highest variation in ADG occurring after meal weaning in the M group only.

Around the time of meal weaning (week nine), in M lambs, there were outliers that managed to maintain a high ADG, so it is possible they were consuming more meal than other lambs (despite gradual weaning occurring over this week along with a significant decrease in average consumption), which allowed this higher ADG to be maintained. But it is unknown if these factors were causing the large differences in ADG among animals. The transition from meal to a pasture-only diet caused the most variation observed over all 12 weeks. It is possible the nature of the two diets affected this. Changing from a grain-based glucogenic diet to a pasture-based lipogenic diet may cause some of the variation seen. The change between these two types of diets requires an adaptation period and there may be a greater growth check in lambs that had previously been consuming large amounts of meal as they transitioned to the pasture-only diet. Notably, there is an adaptation period for rumen microflora and metabolism during the shift from a grain to a forage diet (Beharka et al., 1998), which may lower lamb growth over this period. There may have been differences in individual lambs' intakes of meal and pasture (discussed above) so some lambs may have already been consuming a more lipogenic diet. More investigations into why there were such different responses between individuals to weaning, particularly of meal, are required to help prevent large weight losses or tailoring of a system to prevent large weight losses.

3.5 Conclusions

In conclusion, the amount of intake and nature of the feeds provided to lambs was likely the major reason for differing growth between treatment groups and among weeks. It was found that the most variation in ADG of lambs occurred in the M lambs after meal weaning, which is likely due to poor adaption to a pasture-only diet. Average daily gain and actual nutrient intakes of ME and CP were used to model theoretical intakes and allowed an estimation of pasture intake to be obtained, which could not be done in the previous chapter. It was seen that after meal weaning, a large pasture intake was required to support M lambs' growth as this was now their only feed source, compared to previous weeks when pasture intake was estimated to be zero. It was noted that estimates of pasture intake are not entirely accurate, as lambs were observed to be grazing when their estimated intake was zero. Estimated pasture intake and time spent grazing decreased in week 12 in conjunction with the decline in ADG, and the reasons for this are unknown and require further investigation. Understanding the reasons for this may allow development or optimisation of the rearing system of feeding meal, so that this large decline in ADG can be avoided.

Chapter 4: General discussion

The purpose of this research was to investigate the impact of feeding or not feeding meal on lamb growth, when providing MR *ad libitum* and early access to pasture, in artificially reared lambs. There are few large-scale sheep dairy farms in New Zealand, but there is growing interest in sheep dairy production and predictions that there will be further significant growth of this agricultural sector (Griffiths, 2015, Peterson and Prichard, 2015). Currently, there is a lack of information available about different artificial-rearing systems that may be used in a New Zealand setting (where lambs are weaned to pasture), which often differs from systems of rearing that are used overseas (where lambs are not weaned to solely pasture), where most of the research into artificial lamb rearing has been conducted.

A trial was conducted to investigate if meal could be eliminated from a system in which MR was fed *ad libitum* and pasture provided before weaning, without compromising lamb growth during transitions. That experiment and the results were presented in Chapter 2. The objective of Chapter 3 was to gain further insight into the relationship between nutrient intake and growth, both between treatment groups and over the experiment within treatment groups. In addition, pasture intakes of the two treatment groups (which were not measured) were estimated and compared, to find if there were any possible differences in pasture intake, and variation in lambs' weekly ADG was described, with the focus placed on weeks when there was large variation among lambs' ADG.

In Chapter 2, it was established that including meal in lambs' diets improved ADG before and after MR weaning, however, once meal was removed from the diet, there was a large growth check. This practice of including meal in lambs' diets is a current system that is used on farm. To my knowledge, no study has followed the same regime as that used in this trial.

The results of this chapter indicated that excluding meal from lambs' diets did not adversely affect their growth to 12 weeks of age.

Chapter 3 involved greater investigation into the relationship between nutrient intake and growth and allowed the changes in growth that were occurring within each transition to be seen, information which was not apparent in the previous chapter. Before MR weaning, it was unlikely that meal intake alone caused the higher ADG in lambs fed meal compared to those not fed meal, as this higher ADG coincided with a significantly higher MR intake. After MR weaning, meal intake allowed high ADG compared to that of the lambs only allowed pasture, likely due to the greater energy density of meal, greater efficiency of utilisation of ME for growth from meal, possible lower maintenance requirement in lambs fed meal, and greater digestibility of meal (De Araújo Camilo et al., 2012, Fennessy et al., 1972, Osuji, 1974, Rattray and Joyce, 1976, Suzuki et al., 2008). However, after meal weaning, lambs that had been previously allowed meal exhibited a large decline in growth rate compared to that in the previous weeks and this continued to decline until week 12, when the experiment ended.

The largest variation in ADG among individuals occurred after lambs were weaned from meal and had been transitioned to a pasture-only diet. Some lambs maintained positive growth rates after meal weaning, while others lost weight. Further research into what was driving these differences in response could be carried out to investigate if differential management of lambs can be implemented to improve performance.

Pasture intakes were estimated in Chapter 3 through calculating theoretical intakes required to achieve the growth rates that were recorded. It was found that there were significant differences in the estimated pasture intakes between treatment groups. Lambs fed meal increased their meal consumption, when both meal and pasture were available, so that it was estimated that no pasture was consumed by that group, while the other group could only consume pasture. It was speculated that the transition from a mainly meal diet to a solely pasture diet caused the large growth check. It is possible this occurred because lambs may have previously been substituting meal for pasture (Vendramini et al., 2006), as shown through the estimated pasture intake of zero, and then required a long adaptation period to the pasture diet, possibly due to a poor rumen environment or lack of cellulolytic bacteria (Beharka et al., 1998, Castells et al., 2013). However, why this growth check did not occur immediately after meal weaning is unclear and requires further investigation.

It was a limitation of this study that no pasture intakes were recorded and investigation into actual pasture intakes of lambs reared with and without meal may allow greater understanding of the reasons for differences in growth between treatment groups. However, there are no practical ways to accurately measure pasture intake of individual animals, and this is an issue that has not yet been solved by scientists (Lippke, 2002). Pasture intake can be estimated using animal performance, which uses energy requirements to estimate what the intake should have been (Macoon et al., 2002). It was this method of pasture intake estimation that was used in this study. Another common method of estimating intake is estimating faecal output and measuring diet digestibility, then using these to calculate intake (Lippke, 2002). This method relies on dietary markers such as chromic oxide to estimate faecal output (Lippke, 2002). Total faecal output can also be measured with collection bags, but bags must be emptied at least once daily, which may disrupt grazing behaviour and is labour intensive (Lippke, 2002). Alkanes from herbage may also be used as indigestible faecal markers, but accuracy of this measurement may depend on the alkane selected and further research into this technique is required (Jonker and

Cosgrove, 2017). The herbage disappearance method can also be used to estimate pasture intake, and this does not require faecal sampling (Macoon et al., 2003). In the herbage disappearance method, intake can be predicted from the difference between pre- and post-grazing herbage masses. In addition to this, herbage growth must be taken into account (Macoon et al., 2003). Plate meter readings were taken to give an indication of the allowance of pasture lambs were receiving, however, they proved inaccurate for estimating pasture intake of lambs and so were not used for this purpose. They were likely inaccurate due to a small number of lambs being kept in large paddocks and herbage growth of ungrazed pasture not being recorded, thus, there was too much error in using the plate meter readings to estimate intake according to the herbage disappearance method.

Another of the major limitations of the study was the lack of individual intakes of MR (once lambs were outdoors) and meal. Replication of MR and meal intakes was recorded once lambs were outdoors, however, future research may benefit from individual intakes of meal and MR being recorded and measurements taken to allow more accurate estimation of pasture intakes. This will allow greater understanding of how the differing nutrition of lambs between systems is affecting their growth. These measurements may also help to explain the reasons for the large variation in lamb growth after meal weaning, and variation at other points of the experiment. However, obtaining individual measurements of MR and meal intake, while lambs are on pasture, is practically very difficult or expensive. Automatic feeders (that can be used outdoors) capable of recording individual lambs' intake of MR and meal would be required, or lambs would have to be kept in separate paddocks.

It was speculated that rumen and metabolic changes may cause some of the differences in growth between the treatments. Venous blood samples have been taken to allow evaluation of these factors and is part of the wider AgResearch study. Insight into these changes when combined with the results reported in this thesis may allow further understanding of the reasons that growth differed between groups that are not explained by MR and meal intakes and the transitions.

The results reported in this thesis can be built on and give an indication of future work that may be required. This experiment used a small number of lambs, so larger-scale testing is required before recommendations about system implementation on farm is required, in addition to analysis into the economic costs of each rearing system. Research into lamb performance beyond the 12-week scope of the experiment are being undertaken, possibly as far as lifetime performance, as some lambs that undergo artificial rearing will be used as milking ewes, so how their early life nutrition affects their lifetime performance may be useful knowledge to contribute to the sheep dairy industry in New Zealand.

The conclusions regarding the ability to omit meal from the diet bear the caveat that a good-quality, unrestricted pasture should be provided. Whether this will always be achievable when rearing lambs on large-scale farms is unclear, and analysis of lamb performance when these stipulations cannot be met may be warranted, as pasture quality and quantity affect animal performance (Waghorn and Clarke, 2004). Therefore, when these requirements cannot be met, it is possible that it is necessary to include meal or other solid feeds into the lambs' diets.

It was concluded in Chapter 2 that meal may not be required to support lamb growth to 12 weeks of age (when good-quality, unrestricted pasture is provided). The results of Chapter 3 did not change this conclusion, although they did allow further speculation that the growth check that occurred after meal weaning was due to a poor adaptation to a pasture-only diet and a previously high meal intake, and was highly variable between individual lambs.

This thesis has highlighted that a simple system employing MR and pasture without meal supplement is a satisfactory system of artificial rearing and does not compromise lamb growth to 12 weeks of age. It has shown the differences in growth between the two different feeding systems, likely as a result of transitions and the different diets, and that pasture intake is likely to be very low in lambs that are fed meal *ad libitum* in addition to pasture. This research has demonstrated that investigations into alternative artificial-rearing systems that are based on a pasture-only post-weaning diet are warranted. Finally, the findings of the research undertaken in this thesis can be taken as pilot studies and investigations in the future into further developing and applying the alternative systems on a large scale are warranted. This work has allowed some potential changes to the current rearing system to be identified. It is possible that in farming systems in the future, meal may be excluded from lambs' diets, which can result in a cheaper and simpler rearing system for lambs.

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