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An investigation into the effects of different housing and
feeding systems on behaviour and milk production of dairy
ewes in mid and late stages of lactation

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Abstract

Comparisons of different New Zealand dairy sheep farm systems are currently lacking. The aim of this study was to evaluate the effects of different management systems on the behaviour and milk production of East Friesian cross-bred sheep at different stages of lactation. Two study groups were evaluated. In study group 1, a mob of 479 mixed-age, mid-lactation ewes were housed 24 h/day, and a separate mob of 473 mixed-age, mid-lactation ewes were managed in a hybrid system (housed between morning and afternoon milkings; grazed lucerne overnight). Both received a total mixed ration (TMR) indoors. In study group 2, a mob of 604 mixed-age, late-lactation ewes grazed pasture 24 h/day, and a separate mob of 452 mixed-age late-lactation ewes were in a hybrid system, grazing pasture overnight. For both study groups, individual milk yield, walking distance, lying time, ambient temperature, live weight, and body condition score (BCS) were recorded. All sheep gained BCS and live weight except the fully grazed late-lactation ewes. For study group 1, fully housed ewes in mid-lactation spent less time lying overall during the day, but more overnight compared with those in the hybrid system, which was likely due to the latter grazing overnight. Lying bout duration was similar between groups, while milk yield was 29% less in housed ewes compared with the hybrid ewes. For study group 2, grazing ewes in late-lactation spent more total time lying each day, had longer lying bouts, and walked further each day than those in the hybrid system. Both late-lactation groups had similar milk yields. Fully-housed sheep showed a positive relationship between daily lying time and increasing ambient temperature ($P=0.07$), however, more detailed weather information would be required to draw conclusions from this. In summary, the hybrid management system seems to improve milk yield in mid-lactation compared with the fully housed system, whereas there was no difference between the hybrid and fully grazed systems in late-lactation. Lying behaviour and walking distances (late-lactation group only) differed among different management systems, however, it is unclear what this means in terms of animal welfare, and warrants further investigation.

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Chapter 1: A review of the dairy sheep industry, and physical and physiological factors affecting sheep milk production

Introduction

Milk is amongst the most-produced and most-valuable agricultural commodities in the world (International Dairy Federation, 2016). Since 1980, global sheep milk production has gradually increased, particularly in developed countries (Boyazoglu & Morand-Fehr, 2001). In 1999, FAO reported that sheep milk represented 1.1% of global milk production from all species (Ugarte et al., 2001), which has increased to 1.3% in 2016 – that is 10 billion litres from 19 million sheep dairy farms worldwide (International Dairy Federation, 2016).

Several factors influence milk production in sheep, including: their genetic background; age and parity; nutrition; body condition; stage of lactation; the number of lambs they give birth to; how their lambs are weaned and when; the frequency at which they are milked; their level of activity; and the effects of the environment they are in. In New Zealand, dairy sheep farming has been a growing industry since East Friesian (EF) sheep were imported to the country in 1992 (Morris et al., 2001). Traditionally, New Zealand sheep are managed under extensive pastoral conditions. In their native country (Germany), however, EF sheep are managed under either intensive indoor, or mixed indoor-outdoor systems. Despite it being almost 30 years since their introduction, little information is available regarding the most appropriate management system for EF-cross dairy sheep in New Zealand.

First, an overview of the dairy sheep industry worldwide will provide background of where many dairy sheep breeds originate and how they are managed in their native climate. This overview will also indicate the source of much research in dairy sheep milk production. The following sections will discuss the parameters effecting milk production in dairy sheep listed above. The dairy breeds considered 'best' for high milk yields are the Lacaune, EF, Manchega, and Awassi (Haenlein, 2007). While these are the major breeds used in sheep dairy farming, an abundance of literature has been published about other breeds to illustrate effects of age, parity, and milking frequency (among others) on milk production.

This literature review outlines the research that has been conducted in dairy sheep breeds worldwide, in which sheep were managed under several different systems. Understanding the factors affecting milk production provides insight into what can and cannot be controlled by farmers. Increasing knowledge of these factors allows farmers to make

educated decisions regarding management of their flock, thus, maximising milk yields and farm profits.

1.1 Overview of the dairy sheep industry

Farming dairy sheep is a traditional practice in France, where the predominant breeds are Lacaune, Basco-Bearnaise, Manech, and Corsica breeds. The Lacaune sheep is the major breed originating from France, and has subsequently been genetically improved over the past 40-50 years (Barillet et al., 2001) for increased milk production potential from 80 L to 270 L per lactation (Berger, 2004). Highly productive breeds other than Lacaune include the EF, Manchega, and Awassi, from Germany, Spain, and Israel, respectively. These four breeds were introduced to other countries to improve productivity of local breeds (Haenlein, 2007). The iconic French Roquefort cheese is produced by 1700 suppliers in France from milk of Lacaune dairy sheep (Peterson & Prichard, 2015). One French farm has been reported to produce 330 L per Lacaune ewe over an average of 210 days of lactation. These ewes were housed during the winter months, and for the rest of the year were housed at night-time during cooler temperatures. This is a similar practise to that which has been reported in Switzerland, where Lacaune ewes were housed during hot summer days and during winter (Peterson & Prichard, 2015).

Mediterranean countries including Greece, Romania, Spain, Italy, and Turkey are responsible for 63% of the global sheep milk production (Manca et al., 2016), of which 95% is made into dairy products such as cheese. Sheep milk has higher protein and fat content than that of goats and cows, making it especially suitable for yoghurt and cheese production (Boyazoglu & Morand-Fehr, 2001; Fuertes et al., 1998). In Italy, the most commonly farmed dairy sheep are Sarda sheep (Manca et al., 2016), which are managed under continuous grazing conditions (Ruiz et al., 2000). Merino ewes are also milked in Italy which produce between 300 and 400 mL per day (Peterson & Prichard, 2015). Spanish sheep dairies are often family-run farms that employ traditional pasture-grazing management systems (Morantes et al., 2017). In an attempt to increase milk production over the past 20 years, Lacaune dairy sheep have been imported into Spain, where they are managed indoors (Ugarte et al., 2001). There has also recently been an increase in cross-breeding of native Spanish sheep breeds with Awassi and Assaf breeds, and it has been reported that a shift to

more-intensive management systems must take place in order to achieve the higher yields that they are aiming for (Ugarte et al., 2001). In Greece, a high proportion of their Karagouniko breed of dairy sheep is farmed in lowland paddocks in harsh environmental conditions that the sheep have adapted to in order to maintain high milk production. Chios ewes are also popular in Greece, where they are usually stall-fed (Sinanoglou et al., 2015).

In the United States, dairy sheep farming is concentrated in Wisconsin, where there was also a dairy sheep research programme at the University of Wisconsin-Madison until 2016 (Thomas & Berger, 2018). As of 2015, there were over 100 dairy sheep farms throughout the United States (Peterson & Prichard, 2015). The EF sheep, originating in Germany where they are commonly managed in either partial or full housing systems (Gräser-Herrmann & Sambraus, 2001), is a common breed used in the United States due to their good prolificacy, milk production, and wool traits. These traits cause it to be considered one of the top dairy sheep breeds in the world (Berger et al., 2004). For this reason, eleven pregnant EF ewes, and four EF rams, were imported into New Zealand in 1992 (Allison, 1995). These sheep came from a flock in Sweden that was under veterinary surveillance to ensure no diseases would accompany them to New Zealand. During the three-year quarantine period, ten of the imported ewes gave birth to 26 lambs, 12 of which were ewes who entered the breeding programme, and had their own lambs at 1 year of age. In 1994, embryos were retrieved from all ewes, producing 200 lambs, and again in 1995, producing 440 more lambs (Allison, 1996). The importation of EF sheep in 1992, therefore, led to the beginning of NZ's commercial dairy sheep industry. In recent years, the New Zealand dairy sheep industry has grown significantly. In addition, Lacaune and Awassi dairy sheep genes have been increasingly incorporated in the dairy sheep industry in New Zealand as well (Piddock, 2018).

In 2018, there were 16 dairy sheep farms in operation in New Zealand (Peterson, personal communication, July 25, 2018). Some of these include Blue River Dairy, (the farming division now separate and known as Antara Ag), Kingsmeade Artisan Cheese, Waituhi Kuratau Maori Trust (now known as Maui Milk), and Spring Sheep Milk Co. (Peterson & Prichard, 2015). In 2014, Antara Ag, milking over 26,000 EF x Dorset ewes, had yields of approximately 300 L per ewe over a 160-day milking period, (McMillan et al., 2014). The milk was predominantly dehydrated and sold as milk powder to overseas markets in Indonesia and China, but was

also made into cheeses (Peterson & Prichard, 2015). Kingsmeade (est. 1996) milk 160 ewes, yielding 150 L each. From this, they produce 8.5 tonnes of artisan cheese each year. Through specific breeding strategies, Kingsmeade have produced arguably the best purebred EF flock of dairy ewes in New Zealand (Peterson & Prichard, 2015). In 2015, Maui Milk milked 4500 EF x Romney ewes, the majority of their milk being exported to Australia, and the rest being made into yoghurt (Peterson & Prichard, 2015). Since then, they have converted a second farm to dairy sheep (Waikino Station), and now milk a total of 5000 ewes over two different farming systems: one in which ewes graze ryegrass and clover, lucerne, and plantain year-round, and the other in which ewes graze outside but are housed in barns during extreme conditions and during lambing. Their flock is comprised of EF, Awassi, and Lacuane genetics (Maui Milk Ltd., 2015). By the year 2030, the target for the dairy sheep industry in New Zealand is to export dairy sheep products valuing over \$200 million per year (McMillan et al., 2014).

While there is an abundance of research regarding sheep dairying around the world, there is significantly less information available on the management of dairy sheep in New Zealand. In particular, scientific evidence is lacking on how best to manage dairy sheep in the traditional New Zealand pastoral farming environment.

1.2 Factors effecting milk production

1.2.1 Genetics

As is evident from the above section, different breeds of sheep have different milk production characteristics. In the past, breeding sheep with desirable milk production traits has led to the evolution and development of specific dairy breeds, including EF, Lacaune, Manchega, and Awassi (Haelein, 2007). These breeds have different average lactation lengths, milk yields, and milk composition (Table 1.1). This is advantageous to dairy sheep farmers, as they can base their management strategies on the expected milking characteristics of their flock (Allah et al., 2011). For example, a higher plane of nutrition must be provided to a flock of a breed with a longer lactation length to support the longer lactation compared with a breed with a shorter lactation (Haelein, 2007).

Along with the milk production characteristics, dairy sheep breeds also have different levels of susceptibility to infections and illnesses. Since foreign breeds of sheep require different management when introduced to new countries, this may be inadequately considered, and so the incidence of mastitis in foreign breeds is usually increasingly observed compared with that in their countries of origin (Ugarte et al., 2001). Chios ewes are, however, more susceptible to contracting mastitis than other breeds in their native country (Greece) (Sinanoglou et al., 2015). It has also been reported that, generally, highly productive breeds, such as Lacaune, more commonly suffer from abscesses and uterine prolapses than do others (Ugarte et al., 2001). Reports from the USA and Europe indicate that EF sheep are more susceptible to suffering from respiratory disease than other sheep breeds (Thomas et al., 2001). As a common practise of sheep dairies is to cross-breed animals to increase productivity, the differing susceptibilities to health problems are an important aspect to consider. This can, however, also reduce the risk of health problems in the mixed-breed offspring. For example, in Spain, cross-breeding local breeds with Awassi and Assaf sheep is common due to their environmental adaptability and low incidence of health problems (Ugarte et al., 2001).

Facial eczema is a disease that affects sheep, cattle, and deer in New Zealand and, more recently, Australia. It is caused by ingesting fungal spores of *Pithomyces chartarum* that proliferate and produce hepatotoxic spores (sporidesmin) in pasture during warm, humid weather (Marasas et al., 1972; Phua et al., 1999). Costly to sheep and cattle farmers, it causes potentially fatal liver damage and photosensitivity, particularly on the face and ears, which is what gives facial eczema its name (Phua et al., 1999). Sheep with facial eczema also have lower fertility (Morris et al., 1991), and in cattle studies has been associated with loss of live weight and up to 25% lower milk production (Cuttance et al., 2016). Various sheep breeds have different levels of susceptibility to facial eczema, and a common practise that farmers use to combat its occurrence in their flocks is to selectively breed for facial eczema resistance, or, alternatively, employ prevention protocols (Morris et al., 2004). Since facial eczema is a disease endemic to New Zealand, it would, therefore, be logical to assume that foreign breeds, not having been exposed to it before, would be more susceptible to it. However, a study comparing EF x Romney lambs with purebred Romney lambs in New Zealand indicated that EF crosses have higher resistance to facial eczema compared with

Romney lambs. Furthermore, the EF sires used in the EF x Romney vs. purebred Romney trial did have variable susceptibility to facial eczema (Morris et al., 2001). Due to such variation in the population, selection for resistance would likely be effective in preventing sheep from contracting the disease.

Table 1.1 Average lactation characteristics of different dairy sheep breeds in their originating countries (*Data for first three columns taken from Haenlein, 2007).

Breed (origin)	Lactation length (days)*	Total Milk yield per lactation (kg)*	Total Fat yield per lactation (kg)*	Average daily milk yield (kg)(source)
Lacaune (France)	165	270	20	1.64 (Berger, 2004)
East Friesian (Germany)	300	632	41	2.33 (Hamann et al., 2004)
Israeli Awassi (Israel)	270	495	33	
Manchega (Spain)	210	300	28	
Sarda (Italy)	200	158	11	
Churra (Spain)	150	150	11	1.008 (Fuertes et al., 1998)

The EF sheep breed is considered to be one of the best dairy sheep breeds in the world, with the longest lactation length and highest total and daily yields (Table 1.1) (Gootwine & Goot, 1996; Hamann et al., 2004). This breed also has a reported prolificacy of 230% (lambing percentage), also making them one of the most prolific sheep breeds (Berger, 2004). Together, these traits make EF sheep an ideal breed for sheep dairying; the high lambing percentage leads to greater milk production, as discussed below, as well as a greater number of lambs able to be used as replacements or sold to other dairy sheep farms. By crossbreeding with breeds not traditionally used for milking, milk yields can be

increased compared with yields of purebred native sheep breeds. For example, EF X Dorset have, on average, double the milk yield of purebred Dorset ewes (Berger, 2004). Litter size has also been increased through crossbreeding local breeds with EF sheep (Hamann et al., 2004). Though, provided that sheep are managed efficiently, the percentage of EF in a cross does not seem to have an effect on subsequent milk properties; no significant difference in milk yield and composition was found between sheep that were 50% EF compared with 25% EF (Berger, 2004). From the 1992 importation of EF sheep into New Zealand, some ewes were bred with Romney sheep, and their progeny studied to determine the production characteristics of EF x Romney sheep. Hoggets that were EF x Romney produced 107 L of milk over 120 days, and then as 2-tooths produced 250 L of milk over 175 days (Allison, 1996). More recently, EF-cross ewes in New Zealand have produced up to 2.5 kg milk/d for the first seven days after lambing (Peterson et al., 2005).

In a flock consisting of all the same breed, total milk yields differ between animals depending on lambing date. This means that ewes lambing earlier have more days in milk over the lactation period and greater total milk yields (Ruiz et al., 2000). The heritability of total milk yield is estimated to be 0.27 (Scholtens et al., 2017b), and lactation length 0.015 (El-Saied et al., 1998). Milk yield heritability in sheep has previously also been estimated to be 0.38 (Petrovic et al., 2005), and the heritability of lactation length more recently identified as 0.13 (Scholtens et al., 2017b). Heritability of milk components, such as protein and fat, is reportedly between 0.4 and 0.5 (Peterson, 2017). Differences in heritability may occur due to different breeds used in investigations, and/or natural variability between individual sheep.

While it has been more than 20 years since the introduction of EF genetics to New Zealand dairy sheep flocks, information is lacking on how to manage these sheep appropriately in order for them to fulfil their potential optimal milk production.

1.2.2 Age and parity

It has been established experimentally that a high degree of variation in lactation length and total milk yield exists within flocks (38% and 42-47%, respectively), largely due to the age of ewes, lambing date, and their parity number (Scholtens et al., 2017a). As seen in Figure 1.1,

total milk yield increases up until the fifth lambing, and then begins to decrease (Ruiz et al., 2000).

Figure 1.1 Effect of parity on total milk yield (L) of Laxta dairy sheep in Spain (Ruiz et al., 2000).

Other studies have produced similar results, such as that of de la Fuente et al. (1996), who reported the highest peak milk yield in the fourth lactation, and both Scholtens et al. (2017a) and El-Saied et al. (1999), reported the highest peak milk yield in the third lactation. Similarly, dairy cattle have the highest peak milk yield in their third lactation, and it has been suggested that both sheep and cows experience this due to the mammary glands still developing during an animal's first lactation (Cappio-Borlino et al., 1997). Primiparous ewes also experience a greater negative effect in daily milk yield when changing from twice-a-day to once-a-day milking, likely due to the same reason (Gonzalez-Garcia et al., 2015). This is discussed further below.

Older ewes' rate of decrease in milk yield during a lactation is higher than that of younger ewes (Ruiz et al., 2000). This is illustrated in Figure 1.2, where the gradient is steeper from the peak milk yield to the end of lactation than that of ewes in their first and second lactations. Figure 1.2 does, however, show a peak in lactation later than in most other trials. In New Zealand, peak milk yield in EF-cross ewes has been reported to be reached at about day 12 of lactation (Peterson, 2017).

Figure 1.2 Average lactation curve of dairy sheep in New Zealand at their first (solid, n=22), second (dashed, n=48), and third or more (dotted, n=52) lactation (Scholtens et al., 2017a).

The point at which ewes reach peak lactation yields also changes depending on their parity. First parity dairy sheep generally reach their peak milk yield later than those in their second, third and fourth lactations, which peak earlier and also have higher peak yields (Ruiz et al., 2000). Conversely, Tsigai dairy sheep in their first lactation have their individual peak in daily milk yield earlier than subsequent lactations, which peak between 20 and 40 days after lambing (Oravcova et al., 2006). This is a potential impact in weaning lambs at different times; if lambs are still suckling dams when they reach their peak milk yield, possible revenue is lost; this is discussed further below. Reports on Valle del Belice sheep in Sicily, however, indicate a later peak in milk yield between 30 and 60 days in milk, which is similar to that of Sarda dairy sheep (Cappio-Borlino et al., 1997; Dimauro et al., 2007). The slight differences in milk characteristics between these two breeds have been attributed to their contrasting management systems; Valle del Belice dairy sheep managed extensively on pasture with unbalanced nutrition for their stage of lactation, compared with Sarda dairy sheep managed more intensively, the environmental extremes controlled, and fed adequately for their lactation (Cappio-Borlino et al., 1997).

Table 1.2 Least-square means of milk component variables in Churra dairy ewes of different parity (Fuertes et al., 1998).

At age 1.5 and 4.5, there was no difference in milk yield (Table 1.2). There was a difference, however, between these ages, indicating that milk yield increased at 2.5 years and stayed higher until sheep reach 4.5 years, when it decreased to what it was at 1.5 years. Total solids increased with parity age from 2.5 years. This supports the above statement that milk yield increases with parity up to between the third and fifth lactation, at which it starts to decrease.

1.2.3 Nutrition

Lactation is the most energy-expensive physiological state, and lactating ewes must consume three-times the energy intake of a dry ewe (Peterson, 2017). Milk secretion and yield are susceptible to changes caused by changes in diet. For example, introducing a new crop into the diet is potentially detrimental, while fresh pasture has a positive effect on milk yield (Peterson et al., 2005). The quality of the feed is important to increase milk yield; poorer quality feed may be utilised to increase body condition rather than increase milk production (Stevens et al., 2018). Sheep milk contains 50% more energy than that of cows (4038-4439 kJ/L compared with 2709-2843 kJ/L, respectively), so dairy sheep cannot be considered smaller cows, and the energy required to make the same amount of milk is much greater. The required amount of metabolisable energy (ME) in the diet depends on the weight of the animal. The total ME requirement of a lactating sheep is comprised of the energy required for maintenance, grazing activity, live weight change, and milk production (Peterson, 2017). The maintenance requirement is the amount of ME an animal must consume to remain at a constant live weight (Nicol & Brookes, 2017). Due to the increased activity and growth of the mammary gland and increased blood flow to the heart, digestive

tract, and liver, the energy requirement for maintenance alone in lactating ewes housed indoors is between 30 and 50% higher than that of dry sheep (Peterson, 2017). To account for live weight change, sheep require 30 MJ ME/kg live weight on top of the maintenance requirement calculated by $0.48 \text{ MJ ME/kg } W^{0.75}$ if sheep are on flat land (where W = live weight), plus the ME required for milk production (Nicol & Brookes, 2017). For example, it is approximated that a lactating ewe weighing 70 kg, suckling twins, losing 60 g/d, requires 27.6 MJ ME/d (Peterson, 2017).

Milk yield and fat and protein content in milk, also affected by diet, are negatively correlated. For example, Italian dairy sheep reportedly have correlation coefficients for milk yield and fat/protein content between -0.33 and -0.54 (Pulina et al., 2006). Since both the volume of milk and its composition contribute to the value of the milk, finding a balance that provides high yields and content of components is essential for optimising revenue (Bocquier & Caja, 1999).

The level of nutrition is positively correlated with milk yield and composition. Table 1.3 shows the consequences of high and low feeding levels during late pregnancy on udder size and milk yield. To ensure optimal milk production, adequate feeding of ewes must begin at least one month before lambing (Cannas et al., 2002; Jordan, 1998). High energy intake in early lactation is associated with a high, early peak in milk yield, while nutrient restriction in late pregnancy and early lactation results in low and late milk yield (Bocquier & Caja, 1999; Cannas et al., 2002). Approximately 70% of lamb growth occurs in the last six weeks of gestation, at the same time as the mammary gland is developing and preparing for producing colostrum (Kenyon & Webby, 2017). Adequate feeding of sheep during late pregnancy is, therefore, also essential for lamb survival, as sheep who gain live weight prior to lambing give birth to larger lambs that stand and locate the udder faster than those that do not (an essential factor contributing to lamb survival) (Everett-Hincks et al., 2005).

Table 1.3 Consequences of high and low feeding levels (FL) from day 140 of gestation on udder morphology and milk yield, averaged over 12 weeks of lactation (high FL=110% of nutrient requirement; low FL=90% of nutrient requirement) (Cannas et al., 2002).

	High FL	Low FL
Udder weight (kg)	2.08	1.46
Udder circumference (cm)	44.4	38.4
Teat length (cm)	4.9	4.3
Mammary gland weight (kg)	1.55	1.15
Total DNA (g)	4.97	2.82
Total RNA (g)	4.97	2.82
Total milk yield (l to 12 weeks of lactation)	114	82
Daily milk yield (l/d)	1.357	0.976
BW variations (kg in first 7 weeks of lactation)	0	+2.4

Under-feeding dairy ewes during lactation leads to the mobilisation of energy stores. The efficiency of converting body energy stores to milk has been established as close to 80% (Bocquier et al., 1999). In early lactation, when milk production is at its highest, ewes are often unable to consume enough nutrients to meet the energy demands for milk production (Cant et al., 2000). Under-nutrition is, in most cases, unavoidable at this time, and fat stores are used. The fat content in milk of under-nourished ewes in a negative energy balance is, therefore, generally higher than those meeting feed intake requirements. In mid-late lactation, severe undernutrition resulted in up to 31% decrease in milk yield, and a 9.6 g/L increase in milk fat content (Bocquier & Caja, 1999). Over-nutrition of lactating ewes in mid-late lactation restores their body energy reserves that they used in early lactation. When energy intake increases, the content of protein in milk slightly increases, while milk fat content decreases (Bocquier & Caja, 1999).

Supplements can be used to increase energy intake, however, if too degradable in the rumen, they may not actually provide much energy to the ewe. Rumen-undegradable protein supplements, such as fish and corn meal, are a better option to increase milk yield by 600 to 940 ml/d (Cant et al., 2000). Feeding fat supplements increases energetic efficiency by upregulating nutrient partitioning in favour of lactation (Pulina et al., 2006). They can be either protected or unprotected from rumen microbial activity. Regardless of the type, increased fat in the diet reduces rumen fermentation, losing the advantage gained by the higher net energy of the diet. Rumen protected fats, however, have these effects to a lesser extent than those unprotected (Pulina et al., 2006). Concentrates in the form of total

mixed ration (TMR) diets can also be added to the diet, thereby increasing both ME intake and milk yield (Peterson, 2017).

Since a high proportion of sheep milk is made into cheese, the milk fat and protein yield is particularly important, as they dictate the subsequent cheese yield. As well as energy balance discussed above, the neutral detergent fibre (NDF) concentration of the diet also has a positive affect on milk fat content when milk yield is above 1.5 kg/d (Figure 1.3) (Pulina et al., 2006). The amount of NDF and crude protein in a forage accounts for between 55 and 80% of its dry matter content (Waghorn et al., 2017). Milk fat content can decline significantly if the diet is too rich in starch and low in fibre, a condition called milk fat depression (MFD). MFD is caused by altering rumen fermentation that causes production of conjugated linoleic acid, a bioactive fatty acid, that inhibits fatty acid synthesis (Peterson, 2017). Protein content in milk is linked to the concentration of energy in the diet, particularly in early lactation (Pulina et al., 2006). Lactating ewes should have a diet with 16% crude protein (Campbell & Marshall, 2016), a measure often exceeded in pasture anyway (Waghorn et al., 2017). Grazing sheep should be offered >2000 kgDM/ha pasture, lucerne, or herb and legume mixed swards (depending on energy and water content of the diet) to meet ME requirements, with any gaps filled by offering supplementary crops (Peterson, 2017). For example, feeding a mix of chicory, plantain, and red and white clover to dairy ewes increased milk production compared with those fed predominantly ryegrass (Peterson, 2016). In milking parlours, concentrates are often fed, however, this should not exceed 300 g/ewe/d, due to the substitution effect (Peterson, 2017; Thomas et al., 2014). Barley and maize grain (containing 13 and 13.6 MJ ME/kg DM, respectively; de Ruiter et al., 2017) are suitable, but reportedly do not result in a response in milk production, which is why supplementary crops, such as chicory (containing 13.1 MJ ME/kg DM; de Ruiter et al., 2017), are more effective to increase energy intake and, thus, milk production (Clement, 2002; Peterson, 2016).

Figure 1.3 How milk fat concentration is affected by NDF concentration in feed in dairy sheep whose milk yield is >1.5 kg/d (Pulina et al., 2006).

Information regarding the most effective way to feed dairy sheep in New Zealand is lacking. Traditional New Zealand farming practise is extensive and pasture-based, however, pasture grazing on rough terrain may not be ideal for EF dairy sheep, as they are often managed partially inside overseas. Given that nutrition is such an important factor influencing milk yield and composition, information on the best feeding strategies for EF sheep in New Zealand is essential in developing feeding and management systems to optimise milk production in New Zealand dairy farms.

1.2.4 Body condition

The body condition score (BCS) of an animal is considered an indicator of its nutritional status, reflecting changes in their subcutaneous layer of fat (Jefferies, 1961; Gonzalez-Garcia et al., 2015). Prior to lambing, ewes should have a BCS between 3.5 and 3.8 (five-point scale; Jordan, 1998). This is to ensure they have sufficient body reserves to make up for the nutrient deficit in the first few weeks of lactation. If BCS is 4.5 or 5, sheep typically eat less, so milk yield is lower in these animals compared with those with lower BCS (Jordan, 1998). After lambing, if lambs are allowed to suckle for three to four weeks, BCS declines (Gonzalez-Garcia et al., 2015). Primiparous, Lacaune ewes used in a recent trial gained BCS once they started being machine milked (Figure 1.4), while multiparous ewes started gaining BCS towards the end of the suckling period. In that trial, single-bearing Lacaune ewes also had consistently higher BCS than that of twin-bearing ewes (Gonzalez-Garcia et al., 2015).

This occurs because ewes with multiple lambs have much higher energy requirements than those of single-bearing ewes, and mobilise energy stores in order to meet those requirements. Ewes should not, however, lose more than 1.0 BCS units within a six-week period, as this can reduce milk production and increase the risk of ketosis (Cannas et al., 2002).

Figure 1.4 Changes in body condition of primiparous (graph one) and multiparous (graph two) Lacaune ewes as they transition from twice-a-day to once-a-day milking (single lamb = ◦; twin lambs = •) (Gonzalez-Garcia et al., 2015).

While changes in BCS throughout lactation have been illustrated previously, changes in BCS in New Zealand sheep dairy farming systems have not been identified.

1.2.5 Stage of lactation

Milk yield decreases as lactation progresses after peaking in the first few weeks of lactation, while the content of fat and protein also increases (Ploumi et al., 1998). In the study by Fuertes et al. (1998), at the end of lactation, milk yield was one third lower than it was at the beginning, but fat and protein contents were much higher (2.3 and 1.5x higher respectively). The decline in milk yield was, however, more pronounced than the increase in fat and protein content. In cases where small differences in milk yield are observed between stages of lactation, the level of feeding is likely the cause (Oravcova et al., 2006). After the peak milk yield in early lactation, yield gradually declines. Lactation persistency refers to the rate at which this decline occurs, i.e., flatter lactation curves indicate better persistency (Cannas et al., 2002).

Average lactation curves of the first two months of lactation in EF sheep in New Zealand, lambing at five different times of year, are seen in Figure 1.5. The time of the peak milk yield

in Figure 1.5 (approximately one week after lambing) is consistent with the timing of peak milk yields obtained in the majority of studies. A similar decreasing pattern is shown in Figure 1.6. Milk yield in mid- and late lactation is affected by the milk yield in early lactation; higher milk yields in the first month increase the milk yielded throughout the rest of lactation, and prolongs the lactation period (Jordan, 1998). Within the first 30 days of lactation, approximately 25% of the total milk yield is produced (McKusick et al., 2001). Throughout the lactation period, mammary secretory cells gradually get smaller and less active via involution. Prolactin and growth hormone, the major hormones maintaining lactation, decrease in circulation as lactation progresses, facilitating involution (Cannas et al., 2002). Growth hormone act by stimulating insulin-like growth-factor I (IGF-I), whose receptors are in the mammary gland. The concentration of growth hormone is usually slightly higher in the first months of lactation, although in sheep it is quite low throughout the whole lactation. Insulin is low in early lactation to prevent the uptake of glucose by peripheral tissues. Growth hormone also reduces peripheral sensitivity to insulin to direct glucose to the mammary gland for milk production. As the concentration of growth hormone declines, sensitivity of the body to insulin increases, so glucose is preferentially used by peripheral tissues. Prolactin acts through the suppression of insulin-like growth-factor binding protein-5, which would otherwise inhibit IGF-I secretion, which in turn would inhibit the action of growth hormone (Cannas et al., 2002).

Figure 1.5 Average lactation curves for the first two months of lactation in EF sheep on one New Zealand farm, lambing at different times of the year (Peterson et al., 2005).

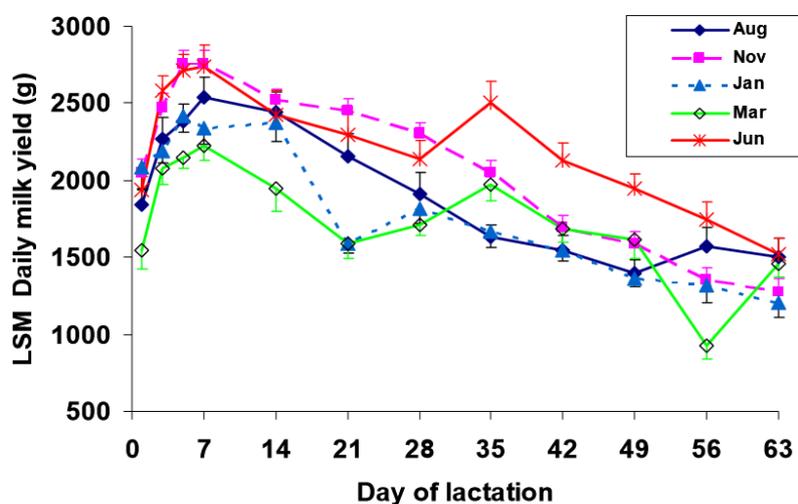


Figure 1.6 Weekly milk yield (•), somatic cell count (■), and lactose content (▲) of individual Churra dairy sheep from two weeks post-partum in Spain (Fuertes et al., 1998).

1.2.6 Number of lambs

It has been well-established that multiple-bearing dairy ewes have higher milk yields than single-bearing ewes of about 10% (Cannas et al., 2002). In a study on Latxa sheep, ewes giving birth to two or more lambs had higher total milk yields (up to 198 L) compared with those lambing singles (up to 175 L), after weaning lambs at 25-30 days of age (Ruiz et al., 2000). A study on Churra ewes presented similar results, with multiple-bearing ewes producing 140 L of milk, while those with single lambs yielded 128 L (El-Saied et al., 1999). Figure 1.7 illustrates that EF dairy sheep in New Zealand, lambing at different times of the year, which have twins have higher daily milk yields than those bearing singles (Peterson et al., 2005).

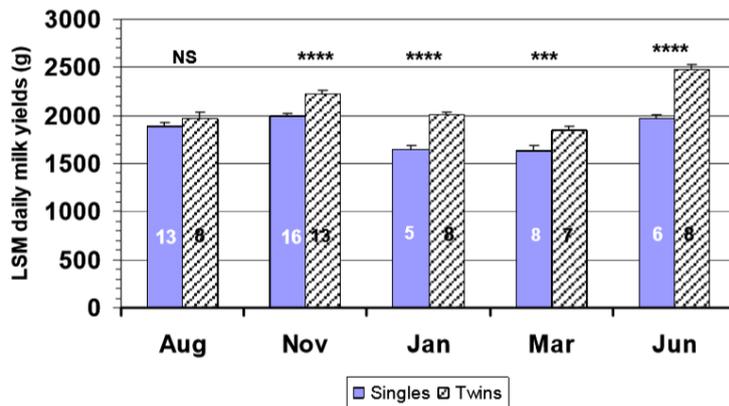
The number of lambs born to a ewe can affect milk yield, somatic cell count (SCC), protein, fat, casein and lactose percentages, and total milk solids percentage. For example, milk yield

measured (including the suckling period before lambs are removed) in ewes bearing three live lambs was 17.9% higher than those bearing single lambs, and 9.1% higher in twins compared with singletons (Fuertes et al., 1998). Similarly, Tsigai and improved Valachian dairy sheep have reportedly higher daily milk yields when giving birth to multiple lambs compared with singles in Slovakia (Oravcova et al., 2006). This occurred due to the increased mammary stimulation by suckling lambs in multiple-bearing ewes (El-Saied et al., 1999). One study reported no difference in milk yield between sheep with different litter sizes.

However, in this trial, the fat yield was larger for sheep bearing three or more lambs than those who had singles (Scholtens et al., 2017a). This is likely due to the increased energy store mobilisation in ewes bearing multiples, as discussed earlier. The correlation between milk yield and litter size is reportedly 0.21, so by selectively breeding for increased milk yield, litter size would likely increase as well, and vice versa (Scholtens et al., 2017a).

Ewes bearing multiple lambs have larger placental weights, and, therefore, higher progesterone and placental mammogenic hormones in late gestation (Cannas et al., 2002). These hormones include prolactin, oestrogen, and placental lactogen (PL). The concentration of PL, secreted by the placenta, increases from day 100 of gestation, and is greater in plasma concentration in multiple-bearing ewes compared with single-bearing ewes due to the larger surface area of the placenta (Forsyth, 1984). Alveolar development is stimulated by PL during gestation, so the more PL present, the more alveolar development that is stimulated, and thus, the more milk sheep produce during lactation (Cotor et al., 2011). Mammary stromal tissue also contains oestrogen receptors which increase in number in late pregnancy, and so it is thought that oestrogen indirectly affects mammogenesis through increasing the proliferation of epithelial cells (Laud et al., 1999). Prolactin, secreted from the pituitary gland, is considered a lactogenic hormone, as it is not necessary for mammogenesis during pregnancy. If it is not present in late gestation, however, the onset of lactation is delayed. Oestrogen upregulates the number of prolactin receptors in the mammary gland in late gestation (Schams et al., 1984).

Figure 1.7 Daily milk yield (g) of single and twin-bearing, non-dairy, EF-cross sheep in New Zealand after lambing at different times of the year (*=significant difference; n for each group provided in each column) (Peterson et al., 2005).



1.2.7 Management systems

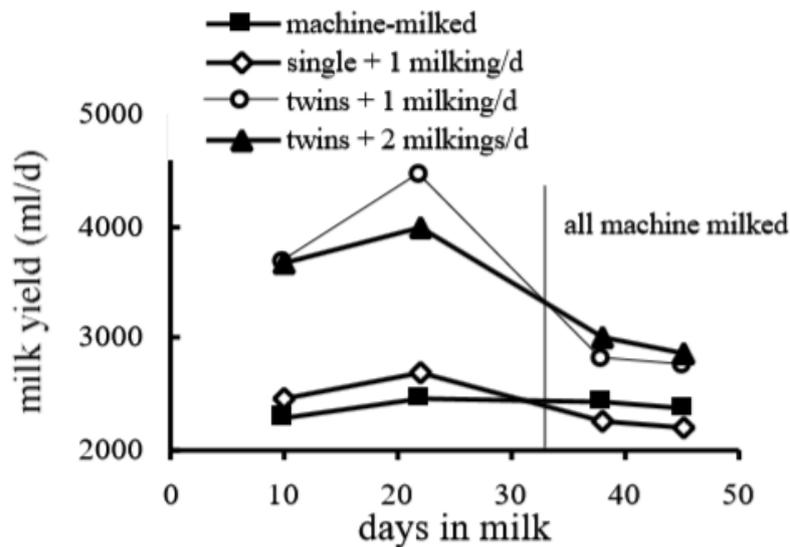
The effect of weaning system on milk production

The age at which lambs are weaned from their dams has an effect on the subsequent milk production of the dams, and also impacts on both lamb and dam welfare. Lambs in dairy flocks often suckle their dam for the first 45-50 days of life before they are weaned, but it is reportedly becoming a more common practise to wean them earlier, at approximately 30 days of age (Napolitano et al., 2008). Milk yields in the first month of lactation account for 25% of the total milk yield over the whole lactation; this when lambs are still suckling in some dairy farm systems (McKusick et al., 2001). For example, Latxa sheep, traditionally farmed in Spain, often lamb during winter and the lambs suckle for the first 25 to 30 days before they are weaned and the ewes are machine/hand milked (Ruiz et al., 2000). In other Mediterranean countries, lambs suckle for one month before weaning (Fuertes et al., 1998). As of 2001 in the USA, the common practise was to let lambs suckle for 30 days or more before milking ewes due to the high costs of milk replacer required to raise lambs (Thomas et al., 2001). This does, however, reduce the revenue accumulated from milking ewes, whose peak milk yield is likely to occur during this time. A study in the USA reported that when EF x Dorset ewes were machine milked, starting 24-36 hours after lambing, their total milk yielded for processing was 240 kg, while those that kept their lambs for 30 days and

then machine milked had 149 kg of milk over the machine milking period (Thomas et al., 2001).

Lambs must be kept with their mothers for at least two days following birth to ensure that they drink sufficient colostrum for their energy and immune system requirements. Studies have shown that dams separated from their lambs earlier have lower total milk yields than dams separated later on (Napolitano et al., 2008). This occurs due to a reduced number and activity of mammary epithelial cells, which increase in number and activity if lambs are allowed to suckle for the first 30 days of lactation (Peterson, 2017). For this reason, milking while also allowing lambs to suckle is used on some farms during the first month or so after lambing, which causes sheep to have higher milk yields (Figure 1.8). Lambs in this management system are separated from their dams overnight and allowed to suckle them during the day (Cant et al., 2000; McKusick et al., 2001). A trial compared the following systems: ewes were machine milked from 24 hours after lambing, 30 days after lambing, and a mixed system where ewes were machine milked from the beginning of the lactation period with lambs allowed to suckle during the day. Results showed that those in the mixed system had the highest peak milk yields (McKusick et al., 2001). Removing lambs from their dams 24-48 hours after birth increases the risk of insufficient colostrum intake, resulting in health problems later, such as scours. It does, however, mean that no milk is lost to lambs drinking it (Peterson, 2017). EF sheep milked from 24 hours after lambing produced 51% more milk than those who were not machine milked until day 30 (McKusick et al., 2001).

Figure 1.8 Total daily milk production by dairy ewes which are either machine milked once or twice-a-day and/or suckled by their lambs in Canada (Cant et al., 2000).



Separating lambs from their dams is a stressful event, as they share a strong bond that develops in the hours after birth. Lambs experience both emotional stress, evident by their increased bleating and movement, and nutritional stress, as they are transitioned from maternal milk to milk replacer (Napolitano et al., 2008). In terms of the welfare of the dam, removing their lambs results in a change in their behaviour, standing with their heads raised, ears erect, bleating, and spending less time resting and ruminating. These behaviours indicate that separation is also an unpleasant event for them as well as for the lambs (Napolitano et al., 2008).

Sheep dairy farms in New Zealand currently utilise both of the weaning/milking systems of allowing lambs to suckle for approximately a month before machine milking, and using a combination of machine milking and allowing lambs to suckle during the day. The most appropriate weaning system depends on the lifestyle of the farmers and how much work and cost goes into raising lambs. It has been suggested that, with the growing New Zealand sheep dairy industry, independent lamb-rearing operations may also be a growing enterprise to remove the monetary and labour expense of raising lambs from dairy sheep farmers (Peterson, 2017).

Milking frequency

Sheep, like cows, can be milked once or twice a day, or every 16 hours (three times over two days). Milking twice a day generally increases milk yield, and changing ewes from twice a day to once a day reportedly decreases milk yield by 5-40%, depending on the breed (Koutouli et al., 2017; Marnet & Komara, 2008). This is because some breeds have mammary glands that have cisterns with a greater capacity to store milk than others (Rovai et al., 2008; Gonzales-Garcia et al., 2015). For example, Lacaune ewes have a larger cistern capacity than do Manchega ewes (Rovai et al., 2008).

Twice-daily milking is the most common practise on large sheep dairy farms. The more frequently a sheep is milked, the more active alveoli they have at their peak alveoli population. In an experiment reported by Dimauro et al. (2007), Sarda dairy sheep milked once per day peaked at 3.89×10^9 active alveoli, milked twice per day peaked at 6.27×10^9 , and those milked three times per day peaked at 7.71×10^9 active alveolar cells. After reaching their peak, involution begins to gradually occur. The higher the peak number of active alveoli, the higher the number of active alveoli that will be present towards the end of the lactation period, i.e., the better milk production persistency of the sheep (Dimauro et al., 2007). Although, in a study that switched EF-cross ewes from milking three times per day to twice per day, there was no difference in milk production compared with those which were maintained on twice per day throughout (de Bie et al., 2000). Therefore, it is beneficial to milk sheep at least twice per day from the beginning of lactation in order to increase the subsequent yields. The rate at which milk is secreted decreases as lactation progresses, so switching to once-a-day milking later in lactation often occurs without negatively impacting milk secretion (Castillo et al., 2008; Thomas & Berger, 2018). Sheep milked once a day are generally in a positive energy balance which allows them to gain BCS.

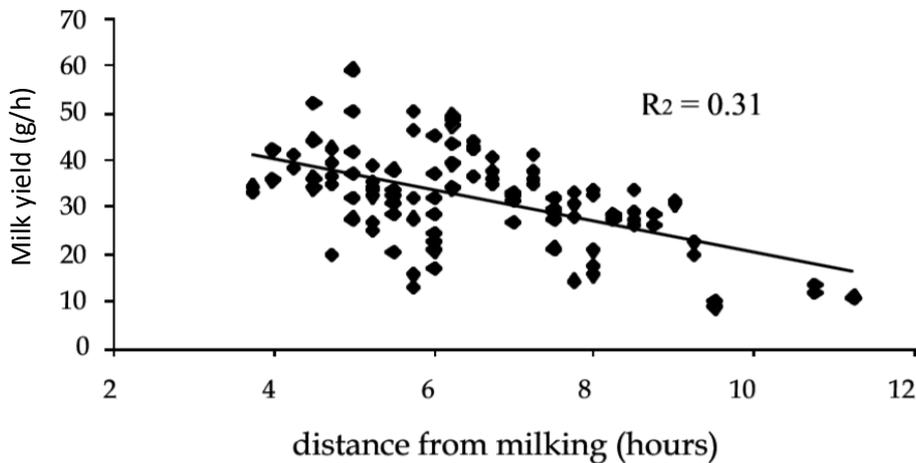
The time of day at which sheep are milked can also influence milk yield, particularly in those milked more than once per day. The interval between milking times, if unequal, results in differences between morning and afternoon milk yields, as seen in an experiment conducted by de la Fuente et al. (1996) in which the average milk yield from morning milking was 25.6% higher than that in the afternoon. Another study in Chios ewes reported similar results (Ploumi et al., 1998). Not only is milk yield affected by the milking interval, but so is the concentration of other milk components, such as protein and fat yield, which

are reportedly higher in the afternoon than in the morning milking (de la Fuente et al., 1996; Ploumi et al., 1998). Sheep milked once per day reportedly produce milk with greater protein and lower lactose content than those milked more frequently (Koutsouli et al., 2017).

The number of active secretory cells decreases between milkings as they become quiescent, the emptying of the quiescent alveoli reactivating milk secretion. The time it takes for alveoli to be reactivated is influenced by the milking frequency as well as the level of milk production. A prolonged period of quiescence (i.e. long milking interval/low milking frequency) may also lead to alveolar apoptosis (Dimauro et al., 2007). The leakiness of tight junctions in mammary secretory cells also influences milk yield, as their permeability increases as alveoli get bigger. In cows, they become leaky after 18 hours, which allows milk components to move in and out of interstitial fluid, thereby decreasing milk yield (Castillo et al., 2008). It is, therefore, detrimental to milk secretion and milk yield to extend the interval between milkings (Figure 1.9). Furthermore, it is hypothesised that prolonging the period between milkings is detrimental to the welfare of sheep due to potential pain and discomfort caused by intramammary pressure and udder distention (Koutsouli et al., 2017).

It is thought that, as milk accumulates in the cistern, autocrine negative feedback inhibits further milk secretion (Marnet & Komara, 2008). This occurs through the secretion of a peptide, feedback inhibitor of lactation (FIL), synthesised in mammary epithelial cells (Cannas et al., 2002). The tolerance of animals to prolonged periods between milkings is breed-dependent, as breeds with larger cisterns are able to store more milk before milk secretion is compromised (Rovai et al., 2008). FIL acts on alveoli, and milk containing FIL is transferred from the alveoli to the cistern until it is at capacity. The time in which FIL is in contact with secretory epithelium in animals with larger cisterns is therefore decreased, and the inhibitory action of FIL reduced (Cannas et al., 2002). Serotonin is also a feedback inhibitor during lactation (Collier et al., 2012). It is found in mammary epithelial cells and milk, and exogenous treatment with serotonin is used to assist in drying off cattle in the United States (Harrelson et al., 2018). Serotonin receptors are found in mammary epithelial cells, and serotonin acts by inhibiting milk protein synthesis and activating epithelial apoptosis. Serotonin is also a vasoconstrictor, and reduces mammary blood flow, thus, reducing milk production (Collier et al., 2012).

Figure 1.9 Milk secretion rate in mammary glands of Sarda dairy sheep in Italy in the hours after being milked (Cannas et al., 2002).



The high milk yields obtained from EF sheep overseas have not yet been obtained in New Zealand flocks. This may be due to inadequate management of the EF-crossbred sheep in the New Zealand environment, preventing them from performing as well as they do overseas. Information is required to determine the most appropriate farming systems for EF sheep in New Zealand to maximise their milk production.

Activity level

Free-ranging animals typically use greater amounts of energy than those that are confined. The energy used to walk and graze pasture could have potentially be used for milk production. Grazing and walking have been reported in studies to account for approximately 45% of daily energy expenditure each, while ruminating and standing having very low contributions (Lin et al., 2011). The terrain and availability of pasture also influences the energy cost of grazing and walking. It has been calculated that an extra 1.0 MJ ME/d is required for maintenance by ewes on easy hills compared with those on flat land, and even more for those on hard hills (Nicol & Brookes, 2017).

At night, walking activity is reduced compared with daylight hours, indicating more time in darkness being dedicated to ruminating and resting rather than to grazing (Lin et al., 2011). Walking activity is reduced in housed animals with high stocking densities, which is likely due to crowding (Caroprese et al., 2009). While animal activity is reduced when they are housed, this may not relate to an increase in milk production due to ewes becoming fat. As

mentioned above, ewes with BCS 4.5 have lower milk yields than those of BCS 3.5. For this reason, it may be beneficial for ewes to engage in exploratory activities in order to maintain a healthy BCS.

Farming systems involving differences in distances walked potentially have an effect on sheep milk production, but differing animal activity levels in different housing systems in New Zealand have not been established. Information on different dairy sheep management systems in New Zealand would be useful to aid in the development of a farming management system to optimise the lactational performance of dairy sheep in New Zealand.

1.2.8 Environmental factors affecting animal welfare and milk production

Heat stress

Heat stress in animals is caused by the combined effects of high temperatures, high humidity, low wind, and a high degree of solar radiation (Schütz, 2011). Sheep body temperature is regulated by balancing metabolic heat production with environmental heat loss, with heat being exchanged at the surface of their body through convection, conduction, solar radiation, evaporation, and infrared radiation (Pollard et al., 2004). When heat production/load exceeds heat loss, animals can experience heat stress. Some animals are more susceptible to heat stress than others, depending on their breed, nutrition level, health status, and age (Schütz, 2011). Water availability, the type of ground surface the sheep are standing on, and physiological state, also contribute to the ability of animals to cope with heat (Pollard et al., 2004). Heat stress in ruminants can cause impaired growth, reduced milk production, and poor reproduction (Marai et al., 2007; Papanastasiou et al., 2015).

In New Zealand, observations have indicated that on a sunny day, sheep will seek shade (Pollard et al., 2004). The degree of solar radiation animals experience greatly affects their ability to thermoregulate (Silanikove, 2000). Dairy sheep have been observed to perform similar shade-seeking behaviours in the Mediterranean under abnormally warm conditions (Papanastasiou et al., 2015; Sevi et al., 2001). This is due to the ambient temperature,

humidity, and wind speed altering the effectiveness of their cooling mechanisms. In particular, high humidity is associated with poorer evaporative cooling efficiency, and higher wind speeds are associated with improved evaporative cooling. Shade removes a significant amount of radiative heat input from the sun, reducing the heat load on the animal (Pollard et al., 2004). Before animals become heat stressed, they alter their behaviour. These behaviours could include: preferably standing in shaded areas; altering their posture and/or adapting their activity level to increase heat loss and reduce heat production (Schütz, 2011); and decreasing feed intake (Schütz, 2011; Sevi et al., 2001). There have been reports of sheep forming close-standing groups with their heads down in attempt to provide shade to each other and reduce the area of their body surfaces exposed to radiative heat (Pollard et al., 2004). Physiological changes to animals' internal environment also occur in order to reduce heat production, as discussed below (Schütz, 2011).

Heat stress has a negative impact on animal production levels (Figure 1.10), but before production is compromised, animals change their behaviour in attempt to cope with the conditions (Schütz, 2011). Observed behavioural changes in sheep experiencing high ambient temperatures and humidity include more time spent near water and preferably drinking water that was closest to the temperature of the air, changing of body postures, and standing/lying in shaded areas if provided (Schütz, 2011). Animals prefer water close to air temperature in warm weather because drinking it promotes heat dissipation and decreases the metabolic heat production (Pereyra et al., 2010). In addition, sheep in the Waikato region of New Zealand have lower grazing activity during high ambient temperatures, and spent less time lying down when no shade was provided compared with sheep provided with shade. In contrast, sheep in Otago, New Zealand had greater lying times with higher ambient temperatures irrespective of whether shade was provided. This could be a difference due to varying humidity levels in these regions, a theory supported by the evidence of sheep in hot, dry conditions having respiration rates of 121 breaths per minute compared with 226 in humid conditions. These measures indicate that heat load is higher with increased humidity (Schütz, 2011). Overall, hot, humid environments appear to result in sheep spending more time standing to increase heat loss from limbs. While in hot, dry environments more time is spent lying down (Pollard et al., 2004).

Figure 1.10 The relationship between maximum ambient temperature (°C) and average relative humidity (RH) and daily milk yield (g) of Mediterranean dairy sheep (Finocchiaro et al., 2005).

Following behavioural changes, physiological changes begin to occur when sheep are exposed to hot conditions. In sheep, these include: panting, a form of evaporative heat loss from the air flowing through the respiratory tract over nasal turbinæ (heat exchangers), sweating, and vasodilation of blood vessels in the ears and face (Pollard et al., 2004). Sheep suffering from heat stress reportedly exhibit an elevated respiration rate (25-30 breaths per minute = basal rate (Pollard et al., 2004); 80-120 breaths per minute = high level of heat stress; >200 breaths per minute = severe heat stress), raised body temperature, and have an increased water intake compared with those not enduring heat stress (Schütz, 2011). The most effective form of heat loss sheep employ is through rapid, shallow breathing, so recording the respiration rate is considered the best indicator of an increased heat load (Marai et al., 2007; Pollard et al., 2004). They also reduce their feed intake and, consequently produce less milk (Figure 1.10) (Schütz, 2011). Feed intake is reduced by thermal receptors sending suppressive impulses to the central control of appetite in the hypothalamus to prevent further metabolic heat production, and due to the slower passage of food eaten through the gastro-intestinal tract (Sevi et al., 2001). Excessive heat exposure also suppresses pituitary hormone secretion and downregulates insulin secretion, which has a flow-on effect of impairing protein utilisation. Protein synthesis is, therefore, unable to

balance protein catabolism, and animals are subjected to a negative nitrogen balance (Marai et al., 2007).

Heat stress in Sarda dairy sheep has been reported to cause a 30% reduction in milk yield, and by 20% in Comisana dairy sheep (Ramon et al., 2016). Milk yield is compromised in this instance due to the decrease in food intake causing body reserves to be mobilised for energy at the expense of milk production (Sevi et al., 2001). The decrease in feed intake is also linked to a reduction in thermogenic hormone secretion from the thyroid gland (thyroxin and triiodothyronine; Silanikove, 2000), both of which lower the basal metabolic rate of the animal, thereby lessening heat production, but having the flow-on effect of lowering milk yields (Pollard et al., 2004).

Heat stress can also lead to impaired reproduction and increase the incidence of low lamb birth weights (Marai et al., 2007; Schütz, 2011). In rams and ewes, fertility declines during periods of heat stress, along with ovulation rate, oestrus duration, conception success, and fetal and placental growth in ewes (Pollard et al., 2004). Observing animal behaviour is, however, the first useful and important tool in determining when animals are beginning to suffer from heat stress before their productivity level starts to decline. Overall, altered behaviours reduce the necessity for a rapid respiration rate and decrease body temperature of sheep in warm environments, thereby preventing reductions in milk yields, growth rates and lamb birth weights (Schütz, 2011).

Heat stress has a negative impact on animal production and animal health and welfare (Schütz, 2011). An indicator of animal welfare is the temperature-humidity-index (THI), a scale used to combine the effect of both temperature and humidity to provide a numerical value for the degree of heat stress (Srikandakumar et al., 2003). Several different mathematical methods exist to calculate and interpret this measure (various equations can be found in Bohmanova et al., 2007), all of which indicate cut-off points as to when adequate animal welfare standards are met (Bohmanova et al., 2007; Marai et al., 2007). Past these points, preventative measures should be put in place to protect animals from experiencing unpleasant conditions (Pollard et al., 2004). Another indicator of animal welfare is animal productivity and performance. Studies have shown that when sheep are provided shade in warm climates, they have improved fertility and productivity (Pollard et al., 2004).

Environmental factors affecting dairy sheep have not yet been evaluated in New Zealand. East Friesian crosses primarily used in New Zealand are typically managed under extensive management systems, exposed to a wide range of environmental extremes. It is possible that this has a negative impact on their milk production, so research into different management systems, in which the environment is controlled, would be beneficial in determining the most appropriate management system for these sheep.

Housing

Dairy sheep overseas are often housed indoors for at least part of the year or day to protect them from environmental extremes (Caroprese, 2008). Any intensive farming system operates with many animals per unit of space in order to maximise overall farm production, however, this reduces the space between animals and the space for walking around (Caroprese et al., 2009). It is generally accepted that increasing the space allowance per animal indoors leads to improved animal welfare (Bøe et al., 2006). Sheep are notoriously fearful and susceptible to suffering from anxiety, but in an appropriate housing facility with adequate space, ventilation, and hygiene, it is thought that housing dairy sheep is advantageous for their health and welfare. Poor housing conditions, however, are detrimental to ewe udder health and reduce welfare (Caroprese, 2008).

In sheep, reduced space leads to a greater frequency of animals exhibiting aggressive behaviours and a higher incidence of diseases, such as mastitis. Housing dairy ewes in barns with a space allowance of one square metre per ewe can lead to increased prevalence of subclinical mastitis and marked reduction in milk yield (Caroprese et al., 2009). Ewes show preference for lying against a wall when housed indoors (Bøe et al., 2006). For housing sheep, therefore, the length of the perimeter of a pen is important in pen-design. Alternatively, leaning posts can be installed to provide more space to lie against.

The pattern of resting behaviour has been used in the past as an indicator of animal social stress. Sheep resting activity is synchronous and continuous. In dairy cows, smaller lying spaces are associated with an increased number of displacements and overall decreased lying time, so these behaviours are likely to indicate discomfort. Accordingly in sheep, when lying space is reduced to 0.5 m² per ewe, lying time decreases and the number of displacements increases (Bøe et al., 2006). The recommended space allocation for sheep in

barns is at least 0.7 m² per ewe, and at least 7 m³ allowed in air space per ewe (Caroprese, 2008).

Allowing ewes to exhibit natural behaviours such as walking and grazing is important for animal welfare and, subsequently, milk production. Studies have found that allowing sheep access to the outside environment during the day, benefits their behavioural needs (Caroprese et al., 2009). Sheep allowed outside during the day are more active due to stimulation of exploratory behaviours, and it has been reported that this also increases their milk production, although not by how much (Caroprese, 2008). Sheep housed in a high-density barn reportedly drank more water compared with those at low density. This is regarded as an indicator of stress, as animals attempt to adjust to their environment, as well as being due to the ambient temperature increasing due to the high stocking density (Caroprese et al., 2009).

In New Zealand, sheep are traditionally managed outside on pasture. This may not be the most ideal management system to optimise milk production in EF sheep due their traditional management overseas in at least partial indoor systems. A comparison of different housing systems has not yet been conducted in New Zealand to determine the effect of housing ewes on animal production and welfare.

1.2.9 Mastitis

Mastitis is defined as inflammation of the mammary gland, causing a reduction in milk yield and change of milk composition (Peterson, 2017). The infection is caused by bacteria (contagious: *Staphylococcus aureus*, *Streptococcus agalactiae*, *Streptococcus bovis*; environmental: *Escherichia coli*, *Pseudomonas aeruginosa*, *Streptococcus uberis*, *Staphylococcus chromogenes*). *Staphylococcus aureus* is the most common cause of clinical mastitis, while environmental bacteria are the most common cause of subclinical cases (Peterson, 2017). Upon infection, the inflammatory response is triggered, and alveoli secrete neutrophils (a type of somatic cell) into the milk (Addis et al., 2016). SCC in milk is a well-known indicator of subclinical mastitis in several species, including cows and sheep (El-Saied et al., 1999). The cause of infection determines how it should be treated, and what precautionary measures should be taken to prevent further infections. Mastitis in dairy sheep is most commonly caused by *Staphylococcus aureus*, which is present on teats and

can be transmitted to other sheep through contact with milking machinery and human hands (Billon & Decremoux, 1998). Good hygiene practice is, therefore, an effective preventative measure of mastitis in dairy sheep (Peterson, 2017).

Somatic cells are the major defence the udder employs against infection, as they contain lysozymes that release proteolytic enzymes, such as elastase and collagenase, to destroy bacteria in the mammary gland (Leitner et al., 2004). Plasmin transferred from the blood into milk is the main proteolytic enzyme, and increase in its activity in infected mammary glands subsequently degrades casein and impairs the coagulation ability of milk (Leitner et al., 2004). This is detrimental when milk is processed into cheese (Albenzio et al., 2004). Sheep milk is penalised when it contains more than one million cells/mL in France (Billon & Decremoux, 1998), and more than 750,000 cells/mL in the United States (Paape et al., 2001). The SCC threshold proposed for subclinical mastitis in dairy sheep is 250,000 cells/mL (Peterson & Molenaar, 2018). Acute mastitis reportedly occurs in 2-3% of dairy sheep in France (Peterson & Molenaar, 2018), but there are no current reports of the incidence of dairy sheep mastitis in New Zealand.

High SCC in milk is also associated with a reduced lactose content, and this is the same as described for dairy cows (Fuertes et al., 1998). Milk yield decreases by up to 30% in sheep with mastitis (Petrovic et al., 2005), and in Israel, subclinical mastitis has reportedly caused a decrease in milk yield by 50% (Peterson, 2017). In cases where only one udder half is infected, evidence suggests that the other gland increases its milk production to make up for the reduced milk yield (Leitner et al., 2004). Decreasing udder health is observed in sheep as they age, evidenced by an increasing SCC with lactation number and age. SCC does, however, decrease as milk yield increases, although this is likely due to dilution. Figure 1.6 illustrates this, where SCC was lowest in week 5, when maximum milk yield occurred. This could be also due to dilution. The SCC in milk also negatively affects the subsequent quantity and quality of cheese made from it (Petrovic et al., 2005; Pulina et al., 2006). This is because as the SCC increases, the rate of proteolysis increases as cheese ages due to higher moisture content in the cheese facilitating proteolysis (Pulina et al., 2006).

Farmers can also breed for mastitis resistance (Petrovic et al., 2005). The heritability for SCC during lactation in dairy cows is between 0.10 and 0.14 (El-Saied et al., 1999). This is similar in sheep, heritability has been estimated to be approximately 0.11 (Othmane et al., 2002).

Due to this low heritability, a more effective way of preventing mastitis is by maintaining good hygiene conditions with appropriate management practises. In a study conducted in the Mediterranean, a mastitis control program was employed in which teats were dipped in iodine after milking, selective dry therapy was used, and ewes with chronic mastitis were culled, resulting in a mean SCC of 229000 cells/ml, which is reportedly a much lower number than that in other flocks of the same breed without a mastitis control program (mean SCC: 749000 cells/ml) (Fuertes et al., 1998; Othmane et al., 2002).

The prevalence of mastitis in New Zealand dairy sheep has not yet been established or associated with different housing systems. Identification of the best management systems to prevent mastitis in dairy flocks is essential to the optimisation of dairy sheep farming in New Zealand.

1.3 Methods of measuring sheep activity used in previous studies

Technologies such as Global Positioning Systems (GPS) and accelerometers have been used in research to investigate grazing and foraging behaviour in extensively managed animals (Hulbert et al., 1998). A GPS works by receiving signals from multiple orbiting satellites to determine its location by interpreting the time taken for each signal to be received, indicative of the distance between each satellite and the GPS unit (Swain et al., 2011). GPS collars can, therefore, be used to track animal movements and activity patterns over vast pasture sizes and rugged terrains. Technologies are progressing such that in the future, these devices will be able to aid farmers and researchers in tracking animal movements and behaviours in real time. In terms of animal management, this has the potential to make positive changes to the way farmers manage livestock and animal welfare due to the increased ease of finding individual animals and identifying animals that require assistance based on the pattern of their movement behaviours (Bailey et al., 2018).

GPS collars began to be used in research on grazing livestock approximately 20 years ago (Turner et al., 2000; Swain et al., 2011). Research using GPS collars over large pastures has allowed assessment of animal grazing preferences and behaviours, and differences in animal movements over rough terrains (Swain et al., 2011). There has also been a study in which GPS collars were used to determine walking distances of sheep over 12-hour periods, evaluating behavioural patterns of sheep at different grazing intensities (Lin et al., 2011).

Other similar studies have used GPS collars to measure animal walking distances over time, using that information to calculate energy expenditure (Brosh et al., 2006; Lin et al., 2011). GPS collars do not apparently irritate or disturb sheep wearing them (Hulbert et al., 1998).

A high degree of potential error exists in GPS measurements. Spatial accuracy of GPS collars (the difference between the GPS-estimated position of an animal and their 'true' position) is reportedly within 5-10 m (Swain et al., 2011). Experimentally, it has been estimated that 15% of GPS-measured daily walking distances can occur due to GPS error, in which animal movement is recorded but they are actually resting (Ganskopp and Johnson, 2007). This error occurs due to satellite error, receiver-clock error, atmospheric distortion, and/or bouncing signals (Turner et al., 2000; Swain et al., 2011). There can also be interference from the environment, including trees, which affect the receiving ability of the GPS unit. More-frequent (e.g., 0.5-s intervals) GPS recordings are more accurate than less-frequent ones (e.g., one-hour intervals), leading to the recommendation that sample intervals of 10 s or less are required for the most accurate GPS recordings (Swain et al., 2011).

Accelerometers are a more-recent development that, in the past, recorded animal head movements, which were used to determine grazing and resting behaviours (Bailey et al., 2018). Nowadays, they have advanced to record movements on three axes. They are able to record different activities such as walking, lying, grazing, standing, and resting, providing a further insight into animal behaviour patterns (Giovanetti et al., 2017). This technology can therefore fine-tune the information received from GPS collars and provide a clearer picture of animal activity pattern. For example, they may indicate the onset of ryegrass staggers in sheep through measuring their change in behaviour (Bailey et al., 2018).

Animal behaviour patterns have been examined using GPS trackers with and without accelerometer devices. Overall animal activity patterns have been studied, including times spent walking, resting, and grazing (Ungar et al., 2005; Augustine and Derner, 2013). These technologies can assist in dairy sheep research in New Zealand to illustrate the behaviours of sheep in different environments. This will possibly provide further insight into the most appropriate management systems for EF sheep in New Zealand.

1.4 Summary

With the New Zealand dairy sheep industry growing, optimal farming management systems must be developed to maximise milk production and ensure good welfare. Most research on dairy sheep has been done overseas, and has illustrated the factors affecting milk production. While the conditions overseas are not the same as in New Zealand, information from these studies, and those that have been undertaken in New Zealand, can provide a basis of knowledge to understand factors affecting sheep milk production. This can then lead to the development of new studies in New Zealand to determine the most appropriate management systems to employ in order to maximise milk yields.

The most widely-used dairy sheep breeds in New Zealand and in other countries are the EF, or EF-cross (crossed with a local breed), Lacaune, and Awassi. This is because EF ewes are considered the best breed for milk production, with average total milk yields of more than 600 kg of milk per lactation in Germany, and prolificacy of 230%. These high milk yields have not yet been obtained by EF sheep in New Zealand. Other factors influencing milk production are age, parity, nutrition, body condition, stage of lactation, number of lambs, the weaning of lambs, milking frequency, activity level of ewes, the environment, and mastitis.

Milk yield generally increases each season up until sheep are in their third-to-fourth lactation, after which it starts to decline. The time at which sheep reach their peak milk yield within a lactation also depends on their parity, first parity ewes peaking later and at a lower yield than those in their second, third and fourth lactations. In most cases, peak milk yield occurs between 20 and 40 days after lambing.

Lactation is the most energy-expensive physiological state, so adequate feeding of lactating ewes is critical to optimise their milk production. In fact, lactating sheep require three-times as much dietary energy than dry ewes. ME requirements are based on animal weight. For example, a 70 kg ewe suckling twins, losing 60 g/d of live weight, requires 27.6 MJME/d. Underfeeding dairy sheep in late gestation negatively affects subsequent milk production. Under-nutrition during early lactation is, however, unavoidable because high-producing ewes are often unable to consume enough energy to meet nutritional requirements at this stage. This is why having a BCS of between 3.5 and 3.8 is important prior to lambing; it

ensures body fat stores are sufficient to make up for the under-nutrition in early lactation. Having a BCS higher than 4.5 is, however, detrimental to milk production, as it causes feed intake to decrease. BCS should not decrease by more than one BCS unit within six weeks to prevent any negative impact on milk yield. Under-nutrition in mid-late lactation decreases milk yield by up to 31%. The diet should be made up to 16% crude protein. Feeding supplements is often done to make up for feed shortages and to boost energy intake, but care should be taken to ensure rumen-degradable supplements are not used in excess for this, as they may not actually provide much energy. If feeding fat supplements, rumen protected fats are better than rumen unprotected fats that reduce rumen fermentation. Diets rich in starch and low in fibre should also be avoided to prevent milk fat depression.

After the peak within the first month of lactation in most ewes, milk yield begins to decline, while the content of fat and protein increases. The higher the peak milk yield, the better persistency of the lactation because more alveoli were activated prior to the peak. Milk yield declines due to the gradual involution of mammary secretory cells upon the decrease in concentration of prolactin and growth hormone in circulation. The number of lambs a ewe gives birth to also affects the number of active alveoli, because in late pregnancy, multiple lambs stimulate continued mammary function to ensure adequate nutrition of the lambs once they are suckling.

The way in which the lambs are weaned differs greatly between farming systems, some being left to suckle for a month before being separated and the ewes machine milked, some separated as soon as 24 hours after being born, and some allowed to suckle during the day and separated at night for at least a month so ewes can be machine milked in the mornings. The most appropriate for a farm depends on the farm itself, and how much time and money the farmer wishes to spend on lamb rearing.

The frequency of milking also affects the number of active alveoli, so it is recommended, for optimal milk yields, to milk ewes at least twice a day in the first stage of lactation. Milk secretion rate decreases after the peak milk yield, so switching to once-a-day milking later in lactation can occur without having a negative impact on milk yield. Switching from twice to once-a-day milking earlier in lactation causes decreases in milk yield, especially in breeds with smaller cistern capacities (which are generally lower-yielding dairy sheep, such as the Manchega). Prolonging the time between milkings impairs milk production due to tight

junctions becoming leaky, and secretion is inhibited by feedback inhibitor of lactation protein in the milk downregulating alveolar secretory activity.

The environment dairy sheep are in can greatly affect their milk yield. Overseas, dairy sheep are often housed indoors at least some of the time to remove them from environmental extremes. Housing sheep reduces energy expenditure by walking, as free-ranging animals expend greater amounts of energy in grazing and exploring. Walking activity is often reduced in housing situations due to higher stocking densities. Heat stress in animals causes a reduction in feed intake and, subsequently, milk production. Housing ewes to prevent problems such as heat stress is, therefore, advantageous for ewe health, welfare, and milk production. The type of housing, however, must be appropriate for sheep, with adequate ventilation and space to prevent aggression and health problems such as mastitis. Mastitis, subclinical or clinical, potentially reduces dairy sheep milk production by up to 50%, and reduces the cheese-making qualities of the milk. It is recommended that sheep houses have at least 0.75m² per ewe and 7 m³ airspace per ewe (Caroprese, 2008). It is suggested that allowing ewes access to outside benefits animal welfare and, therefore, milk production, as it allows them to perform behaviours such as grazing and exploring. To prevent mastitis, good hygiene practises in the sheep living environment and milking parlour should be upheld to limit the transmission of bacteria among sheep, and reduce the bacteria present to infect sheep udders.

While all of this information is important in determining the best possible management strategies for dairy sheep in New Zealand, key information is missing. EF-cross dairy sheep are predominantly used on New Zealand dairy sheep farms, however, research on these breeds in New Zealand is limited. Because the EF breed is not native to New Zealand, this information is critical to increasing the understanding of how they cope with the traditional New Zealand pastoral environment. How their milk production is affected by different nutritional strategies must be investigated, as does their BCS before and during lactation, the lamb weaning system options in New Zealand, and why, even milked twice-a-day, the maximum milk yields obtained overseas have not been met in New Zealand. This information will aid in developing the most appropriate housing system is for managing this breed in the varying New Zealand environment.

Chapter 2: The impact of dairy sheep nutrition and housing on animal health, welfare, and milk production.

The majority of this chapter has been published in the New Zealand Journal of Animal Science and Production (Bliss et al., 2018).

Introduction

In New Zealand, the dairy sheep industry has expanded significantly in recent years (Peterson & Prichard, 2015). New Zealand sheep are largely farmed in outdoor, pasture-based systems, but the majority of international work has evaluated indoor and mixed indoor-outdoor sheep dairy systems. There is currently little information on how to optimise outdoor systems for sheep dairying.

In summer, farms in warm regions with no irrigation face challenges of limited shade, high solar radiation and ambient temperatures and decreasing pasture quality and quantity (Di Grigoli et al., 2009; Litherland et al., 2002), making animals more susceptible to heat and nutritional stress, and dehydration (Alamer, 2004). Providing housing for ewes may mitigate the negative effects of warm weather, while allowing farmers to control diet quality and quantity (Caroprese, 2008; Di Grigoli et al., 2009). Housing provides shade, while also reducing walking distances to and from the milking parlour, which may decrease energy expenditure and increase available energy for milk production. Indoor and mixed indoor-outdoor systems, therefore, allow farmers to feed ewes a diet of high nutritive value, and may improve aspects of animal welfare (Di Grigoli et al., 2009, Morand-Fehr et al., 2007). There are, however, some reports of lower welfare in housed systems, mostly due to poor housing design and management practise (Caroprese, 2008).

Many factors influence ewe milk production, including breed, nutrition, environment, and behaviour, including activity levels (Haenlein, 2007; Morand-Fehr et al., 2007; Schütz, 2011). Studying animal behaviour, including activity and resting behaviour, under different management conditions can increase knowledge of how ewes interact with their environment, and help assess their level of welfare. For example, sheep prefer to lie on softer flooring compared with hard surfaces (Gordon & Cockram, 1995; Færevik et al., 2005) and lying behaviour is also influenced by factors such as climate conditions (Pollard et al., 2004) and social environment (Bøe et al., 2006).

This study aimed to investigate the effects of different management systems on behaviour and milk production of ewes in different stages of lactation. We hypothesised that, for study group 1, housing animals in mid-lactation 24 h/day would reduce walking distance but would not affect milk production compared with those housed only during the day. In

addition, we hypothesised that fully housed ewes would spend more time lying down than those in the hybrid system due to feed being more easily obtainable. For study group 2, we hypothesised that housing late-lactation ewes during the day would increase milk production compared with those fully grazed on pasture. In addition, we hypothesised that fully grazed ewes would spend less time lying than those in the hybrid system due to more time needed for grazing activities.

2.1 Materials and methods

This study was reviewed and approved by the AgResearch Grasslands Animal Ethics Committee (approval number 14081).

2.1.1 Animals and management systems

This trial took place from December 2016 to February 2017 on a commercial dairy sheep farm near Taupo, New Zealand using East Friesian (EF) cross-bred ewes, aged from one to eight years of age.

To evaluate the impact of housing and feeding systems on behaviour and lactation in ewes in mid-lactation (study group 1, between 25 and 100 days in milk (DIM)), a mob of 952 ewes were randomly allocated to one of two groups: 1) fully housed 24 h/day in a dedicated barn ($n=479$; live weight 70.9 ± 0.4 kg; body condition score (BCS) 4.1 ± 0.02), and 2) a hybrid management system; housed indoors between the a.m. and p.m. milkings (7 a.m. – 1 p.m.) and grazed lucerne overnight ($n=473$; live weight 69.9 ± 0.4 kg; BCS 3.8 ± 0.03). While indoors, ewes in both groups were offered a total mixed ration (TMR) diet.

To evaluate the impact of housing and feeding systems on behaviour and lactation in late-lactation (study group 2, >100 DIM), 1056 ewes were randomly allocated to one of two groups: 1) fully grazed 24 h/day on ryegrass and clover mixed sward pasture ($n=604$; live weight 72.7 ± 0.6 kg; BCS 4.2 ± 0.02), and 2) a hybrid management system; housed indoors between the a.m. and p.m. milkings, and grazed pasture outside overnight ($n=452$; live weight 72.2 ± 0.4 kg; BCS 4.3 ± 0.04). While indoors, ewes in late-lactation in the hybrid system were offered TMR. Water was always available.

The housing barn (Figure 2.1 and Figure 2.2) had a vented canvas roof and open sides to maximise air flow. Each treatment group was managed in one pen (120 x 9 m) while

indoors. Each pen had deep-bedded (approximately 30 cm), kiln-dried wood chips as bedding material (Figure 2.2). Water was provided *ad libitum* in six 2-m long troughs per pen, accessible from each side. In the barn, feed (silage and concentrate, TMR; 2 kg ryegrass and lucerne silage plus 250 g grain-based concentrate supplement of canola, barley and soy meal per head) was offered on concrete pads after each milking, accessible along both sides of each pen, providing feeding space of >45 cm/head. An additional 250 g of concentrate was offered during milking to all ewes irrespective of their treatment group. Grazing available to mid-lactation ewes was lucerne (*Medicago sativa*), provided overnight in paddocks about 500 m from the barn. By calculation, this provided approximately 50% of the ewes' diet. The grazing available to late-lactation ewes was ryegrass/clover (*Lolium perenne*/*Trifolium repens*) mixed-sward pasture, either overnight or continually. The onset of a period of dry weather required use of supplementary feed in the fully grazed group. Pasture made up approximately 55 and 60% of the diet in the hybrid and fully grazed groups, respectively. No natural shade was available in the paddocks.

Figure 2.1 The housing barn used to house ewes in mid-lactation either full-time (n=479) or during the day (n=473), and ewes in late lactation during the day (n=452) in Taupo, New Zealand, over summer.



Figure 2.2 Inside the housing barn with kiln-dried wood chips as bedding.



The study period consisted of a three-week transition period (in which animals were in their respective study groups, but data not used in the analysis to allow for the animals' adjustment to the change in management system), and a 47-day measurement period. Replication of treatment groups was not possible due to limitations on the farm.

2.1.2 Milk yield, body condition score, and live weight

Individual milk yields were recorded automatically by in-line milk meters on three occasions before the trial started to establish a baseline for each group, and on 11 days spaced randomly over the trial period of 47 days (post-transition). Technical issues with the in-line milk meters prevented collection of individual daily milk yield on some days. Therefore, only sheep with milk yields from a least one day prior to the trial start, and four days within the trial period, were included in the analysis.

Ewe live weight and BCS (five-point scale; Jefferies, 1961; Jordan, 1998) were recorded at the start and end of the trial by a single operator.

2.1.3 Walking distance and lying behaviour

Walking distance, a proxy for relative energy expenditure (Osuji, 1974), was calculated from data collected using global positioning system (GPS) units (Enertrol Limited, 2009; accuracy

± 10 m) that recorded location every minute for two weeks (days 23-36 of the trial). Only late-lactation treatments, where the largest difference in walking distance was expected, were monitored because only 10 collars were available. Five GPS collars were allocated randomly to ewes within each group. A high degree of potential error exists with GPS measurements (Ganskopp & Johnson, 2007; Swain et al., 2011). To establish the static error of GPS coordinates, location data from two GPS units placed in the barn and two placed in a paddock were recorded for 24 hours.

Accelerometers (Onset Pendant G data logger, Onset Computer Corporation, Bourne, MA, USA) were used to measure continuous lying behaviour in each system. The data loggers were validated by visual observation prior to the trial in a pilot study in which seven lambs each had one data logger attached to their hind leg. Each logger was set on a logging interval of one minute, recording g-forces on the x- and z-axes. To make all values positive, a value of 3.2 was added to all recordings. Video observation of the lambs was undertaken by one person over a 24-hour period, recording standing/lying behaviour of each animal. Using R (R version 3.5.0, 2017), a random forest model was run on the dataset to determine the appropriate recorded estimates for when sheep are standing up or lying down. Standing was defined by an x-axis value of < 2.7. Accuracy of this cut-off point was then tested by running it against 25% of the data, which proved to be 98% accurate.

The data loggers were placed in a durable fabric pouch and attached with velcro on the side of the hind leg above the metatarsophalangeal joint. A total of 20 ewes in each treatment group were monitored; i.e., for both mid- and late-lactation study group comparisons. Animals were selected by fitting loggers to approximately every 20th ewe in each group during milking. Lying and standing times were recorded continuously for two weeks (between days 23-36 of the trial) using the data loggers set to record the y- and z-axis at 60-s intervals. Lying information was extracted from raw data in Excel, correcting for single events.

2.1.4 Weather

Six temperature and humidity loggers (EI-USB-2-LCD+, Lascar Electronics Ltd. Salisbury, UK) were attached to six pillars, located evenly around the housing barn. They recorded the temperature and humidity of the airspace they were in every half hour for the duration of

the trial. Five of these loggers were placed on pillars which were exposed to direct sunlight at different times of the day, rendering their data unreliable as an indicator of temperature in those areas of the barn. They were, therefore, excluded from analysis, and the one remaining logger used and assumed to represent temperature and humidity of the whole barn.

Outside temperature data was retrieved from the NIWA Virtual Weather Data for NZ application (after failing to retrieve more detailed data from a weather station near to the farm).

2.1.5 Statistical analysis

As a case study, the data is presented with descriptive statistics that describe the variation within each group. Comparison between groups does not necessarily reflect true treatment differences as the treatments were not independently replicated.

GPS data was quality-checked using R (R version 3.5.0), removing any outliers by first making box plots of total walking distance per hour per sheep, and setting an upper limit for each of these totals, defined as

$UQ + 1.5 IQR$

where UQ is the upper quartile and IQR is the inter-quartile range.

Outliers were replaced by the maximum value for that individual on that day. Total distance travelled per hour per sheep was calculated. The average distance per hour was then calculated for each mob. Static testing of GPS measurements showed that location when outside or inside varied by an average of 0.5 and 2.02 m per recording, respectively. Data were corrected for these error values by reducing hourly average walking distances by the displacement error associated with whether sheep were indoors or outside during that hour. The contribution of horizontal walking distance to daily energy expenditure of the late-lactation groups was calculated using the estimate of 2.47 J/kg/horizontal metre (Clapperton, 1964).

Lying behaviour (daily averages for each group), recorded by accelerometers, was calculated as number and duration of events and total lying time, excluding milking periods (4-7 a.m. & 1-4 p.m., as with GPS data). Summaries of BCS and live weight were calculated from the raw

data. Hybrid ewes were indoors between 7 a.m. and 1 p.m., and outside between 4 p.m. and 4 a.m.

Daily milk yield data were summarised by first identifying the variation in yield among animals within each mob, and then taking the natural logarithms of the data to normalise the variation. Means of the logarithms for each day for each mob were fitted to a model using REML (Corbeil & Searle, 2012) and a first-order auto-regressive error, correcting daily milk yield means for the ewe live weight at lambing, the days in milk (within each lactation group), and ewe age.

Due to the limited data from the outside weather information source, maximum ambient temperatures inside and outside were taken from the days during which accelerometers were attached to the ewes. The time at which maximum temperatures were recorded outside was not available from the data source, so only the fully housed and fully grazed animals could be used in this analysis. Using Microsoft Excel, a line graph displaying the maximum temperature against the average total lying time per day for each of the two groups was generated.

2.2 Results

2.2.1 Study group 1

Milk yield. Prior to the transition period, mid-lactation ewes had similar milk yields, as measured on three separate days (approximately 1.0 ± 0.08 L/d, Figure 2.3). During transition, while no milk yield measurements were available from in-line milk meters, it is assumed that this is when the divergence of average daily milk yields occurred due to milk yields differing between groups at the end of the transition period. Over the trial period, milk yield was recorded on eleven different days. Ewes in the hybrid system had 29% greater daily milk yields, on average, than ewes fully housed.

Lying behaviour. During the day, mid-lactation ewes in the hybrid system spent 35% more time lying down, on average, than those fully housed, due to lying down more often (Table 2.1). Overnight, the ewes fully housed spent 83% longer lying down than did hybrid ewes. At this time, lying bouts of ewes in the hybrid system occurred 30% less often and average

bout duration was 16% shorter than that for ewes fully housed. Total lying time was longer for fully housed than for hybrid-system ewes.

Lying behaviour is only compared with ambient temperature in the fully-housed mob (Figure 2.6). The maximum temperatures in the barn exceed the maximum temperatures outside on most days. Days in which the maximum temperature in the barn was higher resulted in longer total lying times compared with when temperatures were lower, indicating a significant positive relationship between lying time and increasing ambient temperature (the correlation coefficient of maximum daily temperature and total daily lying time was 0.48, the slope of the regression line = 5.30, $P=0.07$). Sheep tended to walk around less inside during hotter days.

Body condition score and live weight. At the end of the trial, fully housed ewes in mid-lactation had an average BCS of 4.4 ± 0.02 , and average live weight 75.5 ± 0.5 kg, which equates to an average daily gain (ADG) of 98 g/day. Ewes in the hybrid system had an average BCS of 4.4 ± 0.03 , and average live weight 75.6 ± 0.4 kg at the end of the trial, equating to ADG of 121 g/day.

Figure 2.3 Average daily milk yields (litres \pm SEM) of dairy sheep in two study groups of two treatment groups each: study group 1: 1) mid-lactation housed indoors full-time, fed TMR, 2) mid-lactation in a hybrid housing system, housed during the day between morning and afternoon milking, fed TMR, grazing lucerne outside overnight. Study group 2: 1) late-lactation ewes grazing pasture outside full-time, 2) late-lactation ewes in a hybrid housing system, housed during the day between morning and afternoon milking, fed TMR, grazing pasture outside overnight. The vertical lines indicate the start and end of the transition period. Negative days are the days after lambing before the transition period began.

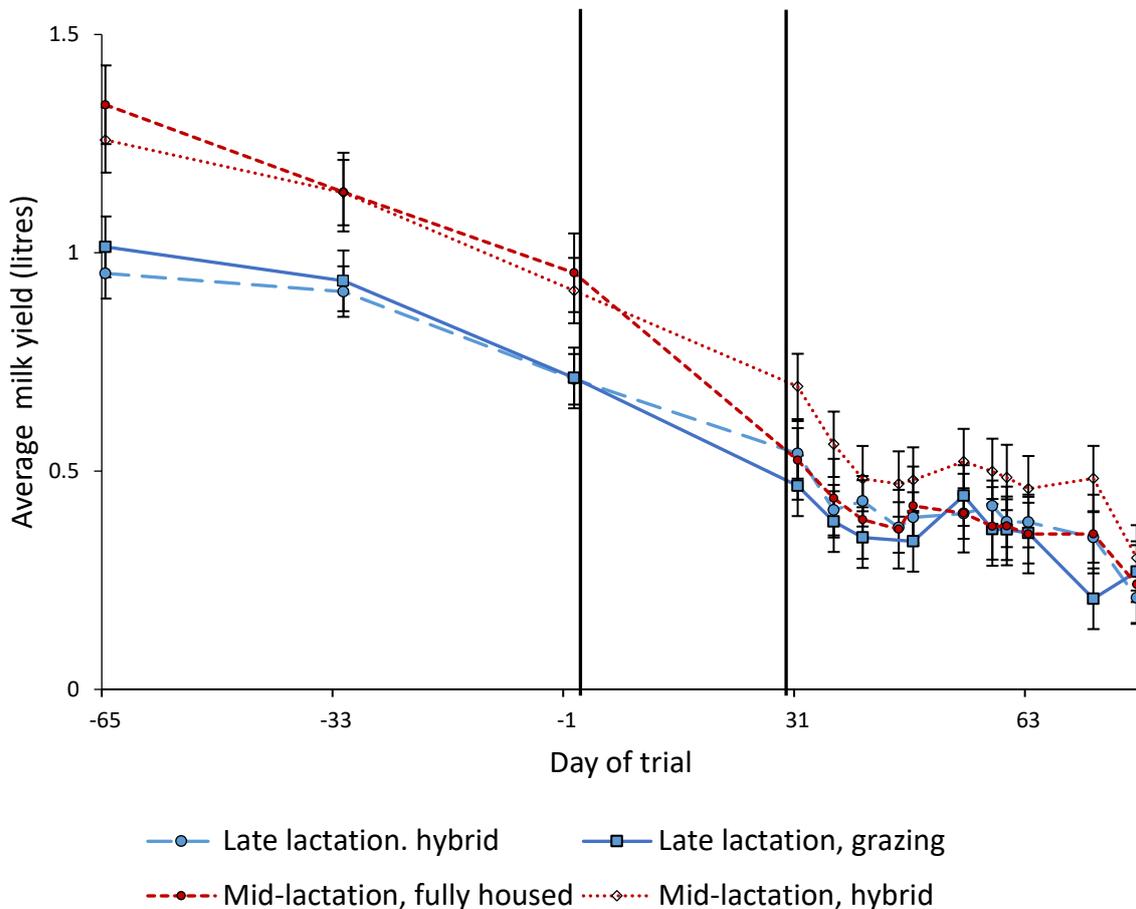


Table 2.1 Average lying behaviour of dairy sheep in different lactation stages and housing systems during the day and overnight, excluding milking periods (4-7 a.m. & 1-4 p.m.), as measured by accelerometers during a two-week period in summer. Values presented are averages \pm SEM.

Lactation stage	Housing system	Time of day	Total lying time (min)	Number of lying bouts	Bout length (min)
Mid-lactation	Fully housed	Day	123.7 \pm 4.1	4.0 \pm 0.1	34.7 \pm 1.6
		Night	474.8 \pm 11.0	10.1 \pm 0.4	51.3 \pm 2.9
Mid-lactation	Hybrid	Day	165.2 \pm 10.1	5.1 \pm 0.3	34.2 \pm 2.1
		Night	368.4 \pm 12.4	7.1 \pm 0.3	61.1 \pm 3.6
Late-lactation	Grazing	Day	171.0 \pm 9.8	3.8 \pm 0.1	49.7 \pm 2.4
		Night	440.2 \pm 13.4	7.4 \pm 0.4	67.3 \pm 4.5
Late-lactation	Hybrid	Day	159.4 \pm 9.9	5.4 \pm 0.3	30.7 \pm 1.2
		Night	396.1 \pm 11.6	6.9 \pm 0.3	62.9 \pm 3.2

2.2.2 Study group 2

Milk yield. The late-lactation groups had similar milk yields prior to the transition period (approximately 0.95 ± 0.08 L/d, Figure 2.3), though milk yield appeared to decline to a greater extent in the grazing group than that in the hybrid group during transition, though, no milk yields were recorded during the transition period. Fluctuations occurred in both groups throughout the trial period in which milk yields were recorded on eleven separate days, but there was no clear difference in average daily milk yield.

Walking distance. Total daily walking distance for the fully grazed ewes in late-lactation was, on average, 35% greater than that of ewes in the late-lactation hybrid treatment (6390 vs. 4730 m, respectively), with walking to and from the milking parlour accounting for a large portion of this (62% vs. 43% of total daily walking distance for grazing and hybrid systems respectively; Figure 2.4). No other difference in average hourly walking distances between grazing or hybrid systems were observed (Figure 2.4). Fully grazing ewes expended more

energy in walking each day than did the hybrid ewes (about 1.14 MJME per ewe/day vs. 0.86 MJME per ewe/day, respectively).

Figure 2.4 Average hourly walking distance (m \pm SEM) of dairy sheep in late-lactation grazing full-time versus those in a hybrid housing system, housed inside during the day and outside overnight, as measured on five ewes per treatment using GPS collars over a two-week period between days 23 and 36 of a 47-day trial. Vertical lines indicate the beginning and end of milking periods in the morning (0400-0700 hrs) and afternoon (1300-1600 hrs).

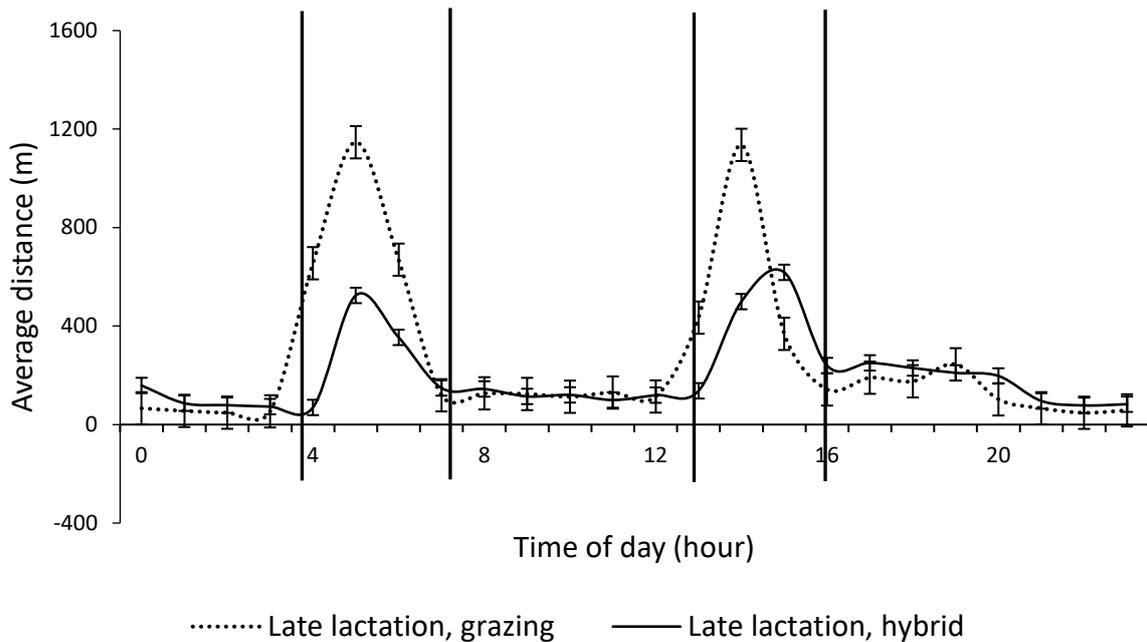
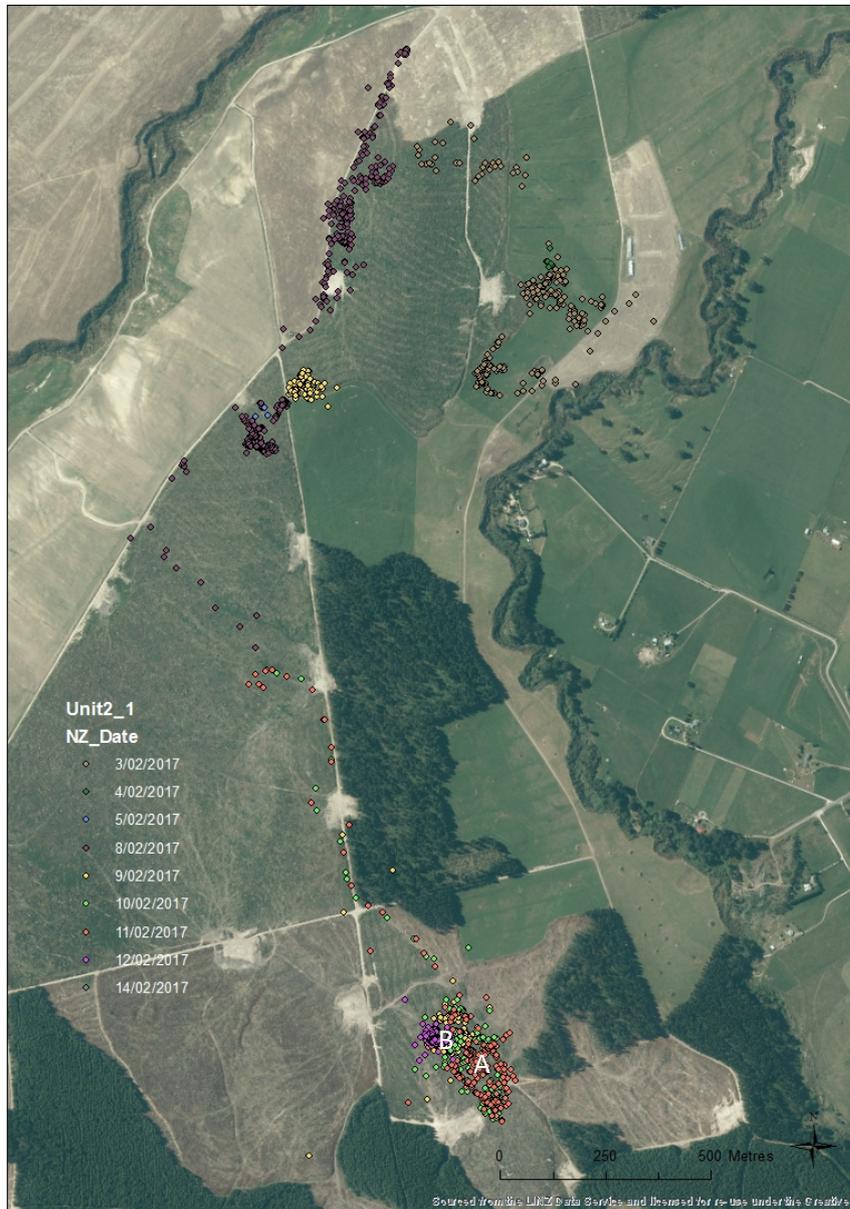


Figure 2.5 A map of the research farm displaying the GPS recordings for one GPS unit attached to a sheep in the fully grazing group for each day (different days indicated by the colour of the location points). The housing barn is located at point A, and the milking parlour at point B. Aerial map shows fence lines of the previous cow dairy farm that have been re-fenced for sheep.

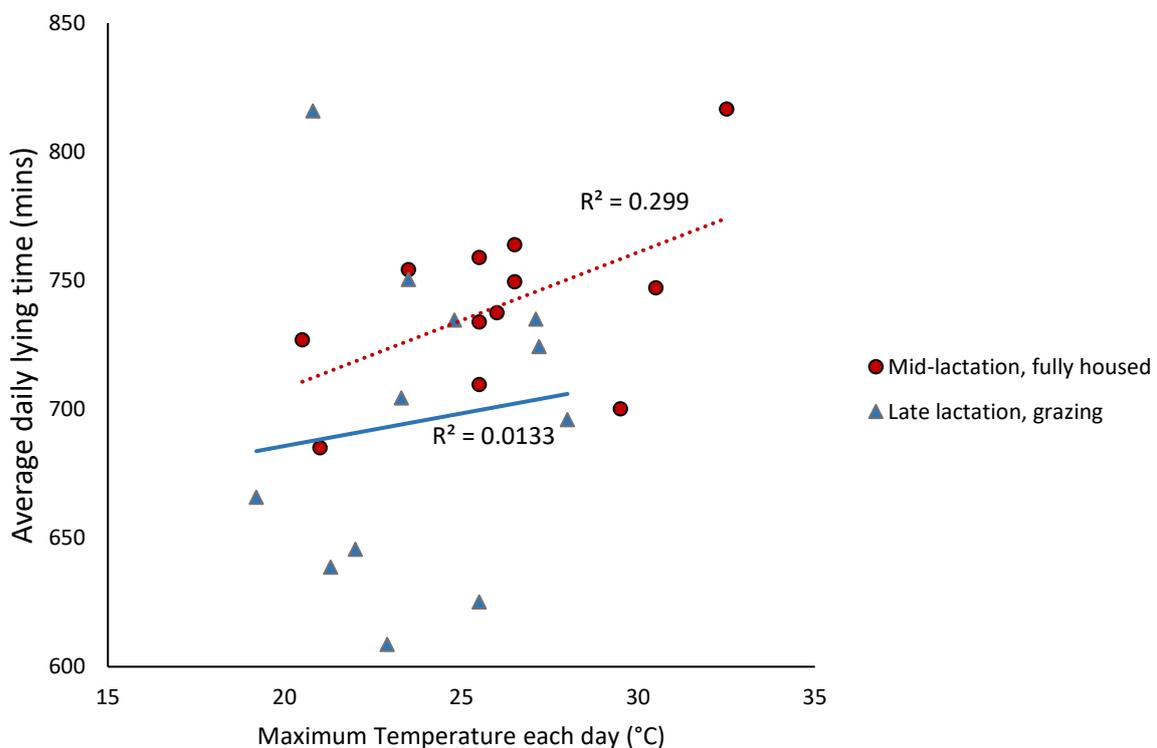


Lying behaviour. During the day, ewes in late-lactation and fully grazing spent 8% more time lying down outside than did ewes in the hybrid system indoors (Table 2.1). The lying bouts of ewes fully grazing occurred less often and for longer periods of time than ewes in the hybrid system. This pattern was greater overnight (12% greater) due to slightly longer lying bouts. Total lying time was longer for ewes fully grazing than for ewes in the hybrid system.

Lying behaviour is only compared with ambient temperature in the fully grazing mob (Figure 2.6). As maximum ambient temperature increased, total lying time per day increased slightly as well, indicating a slight, but positive, relationship between lying time and increasing temperature (the correlation coefficient of daily maximum ambient temperature and total daily lying time was 0.12), but the slope (slope = 2.53) of the regression line was not significant ($P = 0.72$).

Body condition score and live weight. At the end of the trial, fully grazed ewes in late-lactation had an average BCS of 4.2 ± 0.03 , and average live weight 72.4 ± 0.6 kg, which represents no change from the beginning of the trial (average live weight 72.7 ± 0.6 kg). Ewes in the hybrid system had an average BCS of 4.5 ± 0.04 , and average live weight 76.2 ± 0.6 kg at the end of the trial, equating to ADG of 85 g/day.

Figure 2.6 Maximum daily ambient temperature ($^{\circ}\text{C}$) in a housing barn (\bullet) and outside (\blacktriangle) versus the average daily lying time (mins) of dairy sheep in late-lactation grazing full-time (\blacktriangle ; solid trendline) and those in mid-lactation housed full-time (\bullet ; dashed trendline), as measured by accelerometers during a two-week period in summer.



2.3 Discussion

Milk yield is influenced by many factors associated with feed, feed intake, and housing, independent of type of system used. In this case study, a difference was observed in milk yields between groups of ewes in mid-lactation, with higher yields in the hybrid system than in the fully housed system. No strong difference in average daily milk yield was observed between grazing ewes in late-lactation and those in the hybrid system. Walking distances, as a proxy for energy expenditure, were greater in the late-lactation full-grazing system, as expected, but milk production, during the experimental period, was similar to that in the hybrid system. While walking distance was not recorded for the mid-lactation ewes, it can be expected that the daily walking distances of fully housed ewes was lower than those in a hybrid system because they were always closer to the milking shed than those outside at night. Therefore, the effect of less walking to and from the milking parlour was not translated into greater milk production.

The walking and lying data provide a mixed message about energy expenditure. Greater daytime lying times of mid-lactation ewes in the hybrid systems (when indoors) compared with those fully housed may have been an attempt to conserve energy as energy expenditure was up to 38.4 kJ/kg/day greater for standing than lying (Chappel & Hudson, 1979; Osuji, 1974). Alternatively, this group may have rested more during the day than those fully-housed to compensate for the proportionally lower lying times at night. However, the overall energy expenditure when accounting for extra walking and grazing (not measured) was likely to be greater in the hybrid than in the fully housed system. This is not reflected in the larger average gain in BCS and live weight observed in the mid-lactation hybrid system, nor in their higher milk yield. This indicates that the nutrition provided in the hybrid system was likely better than that of sheep housed full-time, which may be related to the portion of the diet that was obtained by grazing lucerne. Ewes from the hybrid system spent less time lying during the night compared with fully housed animals and we speculate that this is partially due to an increased motivation to graze the outside diet.

There are great limitations regarding the weather data from this study. While greater lying times were observed in both the fully-housed and grazed groups at higher daily maximum temperatures, further information is required to determine the reasons behind this

observation (such as humidity). Pollard et al. (2004) reported increased lying times while sheep were in hot, dry environments compared with hot, humid environments. In this study, maximum daily temperatures were higher in the barn than they were outside. Housed sheep showed a stronger relationship between lying time and maximum ambient temperature than those outside (correlation coefficients between maximum daily temperature and total daily lying time for fully-indoor and fully-grazed sheep being 0.48 and 0.12, respectively), so the indoor environment was potentially less humid than the outside environment. Without information on humidity in each environment, it is impossible to draw any conclusions.

Sheep managed outside are likely to be able to perform a wider range of natural behaviours, such as grazing and foraging, compared with sheep kept indoors (Caroprese, 2008; Sevi et al., 2009). Expression of natural behaviour is an important aspect in animal welfare assessments (Bracke & Hopster, 2006). In this trial and in contrast with our predictions, sheep managed on pasture full time had the longest lying times in total (lowest number of lying bouts but the longest bout durations). When the sheep were housed indoors, they had relatively shorter lying bouts compared with when on pasture, which may indicate some disturbance of normal lying behaviour. The difference in lying behaviour may have occurred due to the diet of each group, as more time is required for pasture rumination than that for TMR. More detailed information (fibre and ME content) on the different diets of each mob is required to investigate this further.

It has been suggested that the effects of the outdoor environment and increased energy expenditure associated with walking and grazing (Osuji, 1974) may influence performance. The 0.3 MJME/d difference in energy expenditure from walking in late-lactation ewes was much smaller than that required to result in the observed difference in live weight change. The average daily gain of 85 g/d in late-lactation ewes in the hybrid system over the experimental period would equate to a requirement of approximately 3 MJ ME/d (Nicol & Brookes, 2017). During the day, there was no difference in corrected walking distance between confined animals and those grazing outside, in contrast to a previous study in which housed sheep walked much shorter distances than those on pasture (Osuji, 1974). However, animals in the study reported by Osuji (1974) were grazing poor pastures, and walking measurements were made based on visual observation. While there was a

difference in recording methodologies between this study and that of Osuji, they both illustrate potential responses to the respective environments. Both late-lactation, fully grazing and mid-lactation, fully housed sheep had the greatest total lying times. This may possibly reflect the more settled nature of sheep habituated to a constant environment. One rationale for housing sheep is to reduce exposure to solar radiation. Lying times can be greatly influenced by ambient environmental conditions (Bøe, 1990) and further information regarding the humidity and wind speed would provide further insight to this.

Ongoing work is exploring how the changes in feeding management (including diet composition) may have contributed to the observed milk yield responses in this trial. Future controlled studies with appropriate treatment replication groups should investigate the effects of different management systems on the behaviour, welfare, and milk production in dairy sheep.

Chapter 3: General discussion

Background

The dairy sheep industry in New Zealand is expanding rapidly. The New Zealand dairy sheep industry was established in 1992 with the importation of EF dairy sheep into New Zealand (Morris et al., 2001). Since then, it has expanded to having 16 large-scale, high-producing dairy sheep farms (Peterson, personal communication, July 24, 2018). Traditionally, New Zealand sheep farms manage their flocks extensively on pasture, however, EF sheep originate from Germany where they are commonly managed intensively in either partial or full housing systems (Gräser-Herrmann & Sambras, 2001). Overseas, EF sheep have produced up to 600 kg milk/lactation (Haenlein, 2007), however, as of 2014 in New Zealand, EF-cross sheep have only yielded 300 L per lactation (McMillan et al., 2014). For New Zealand to reach the goal of exporting \$200 million worth of sheep dairy products by 2030 (McMillan et al., 2014), research is required to develop optimal farming systems to maximise EF-cross milk production in New Zealand.

Studies in New Zealand evaluating different feeding and farm management systems on EF-cross sheep provide information to assist in the development of appropriate farming systems to optimise animal performance. Lactating sheep require three times the energy intake than that of dry ewes, so adequately feeding dairy sheep is essential for maximising their milk production (Peterson, 2017). Under-nutrition is unavoidable in early lactation when sheep are unable to physically consume enough feed to meet the high energy requirements of early lactation (Cant et al., 2000). Increasing energy intake prior to lambing ensures sheep have adequate energy stores to make up for the energy deficit experienced in early lactation. Sheep should not lose more than 1.0 BCS units during early lactation, so even though under-nutrition is unavoidable, sheep should still be fed a high plane of nutrition at this time. In mid-lactation, under-nutrition causes a decrease in milk yield (Bocquier & Caja, 1999). Appropriate supplements can be used to increase energy intake, such as fish and corn meal (Cant et al., 2000), as well as supplementary crops such as chicory and plantain (Peterson, 2016). Concentrates such as barley and maize grain should not be offered in excess of 300 g/ewe/day, as they do not result in increased milk production (Clement, 2002; Peterson, 2016). The most appropriate feeding of EF-cross sheep in New Zealand to optimise milk production is currently being investigated.

The way in which sheep are housed affects their activity level and milk production, as well as their health and welfare. Grazing and walking account for 45% of daily energy expenditure in sheep (Lin et al., 2011). Free-ranging animals use greater amounts of energy in exploratory and grazing behaviours than those confined. This energy could otherwise be used for milk production, therefore, housing dairy sheep presumably would lead to increased milk production compared with grazing sheep. This is, however, not necessarily the case, as when ewes become over-fat, reaching BCS of 4.5 or more, they have lower milk yields than those with BCS 3.5 (Jordan, 1998). Allowing dairy sheep to graze outside, therefore, may be beneficial to maintaining BCS at around 3.5, thus maintaining higher milk yields than those with higher BCS. Global positioning system technology has been used to illustrate differences in walking activity between groups in different housing systems to determine if this influenced dairy sheep milk production or not.

In housing dairy sheep, care must be taken to ensure space requirements are met. Each sheep should be provided at least 0.75 m² floor space and 7 m³ airspace to avoid aggression between sheep and reduce the incidence of airborne diseases (Caroprese, 2008). Mastitis also occurs more frequently in dirty living conditions, a disease which decreases milk yield by up to 50% (Peterson, 2017). Hygiene practises in both the housing barn and milking parlour are therefore imperative to the prevention of mastitis in dairy flocks (Peterson, 2017). Housing barns also require ventilation to reduce excessive heat load on animals from crowding, as heat stress is detrimental to both sheep milk production and welfare (Marai et al., 2007; Schütz, 2011). As ambient temperature increases, daily milk yield decreases (Figure 1.10) (Finocchiaro et al., 2005). Animal behaviour is considered an indicator of social stress, such as resting behaviour; decreased time lying down indicating potential discomfort (Bøe et al., 2006). Accelerometers attached to animals are able to record behaviour such as lying and standing (Giovanetti et al., 2017), and have been used to assess the difference in behaviour of dairy sheep in different housing systems.

3.1 Key findings

Milk yield of sheep in different housing systems

Sheep in mid-lactation had a larger response in milk production when housed in different conditions compared with those in late lactation. Housing ewes in mid-lactation during the

day, allowing them to graze overnight, showed increased milk yield by 29% compared with those who are housed in a barn full-time. In contrast, no difference in milk yield was observed between sheep in late lactation grazing full-time compared with those housed during the day and grazing outside at night.

Walking distance of sheep in different housing systems

Sheep grazing pasture full-time walked further each day than those housed in a barn during the day. This occurred largely due to the increased distance between paddocks and the milking parlour compared with the shorter distance between the housing barn and milking parlour. More energy was likely used in grazing behaviour of sheep grazing full-time compared with those who were only allowed to graze overnight. No difference in milk yield was observed between these groups, indicating that animal activity in different housing systems did not affect milk production in late-lactation.

Lying behaviour of sheep in different housing systems

Ewes in mid-lactation housed during the day and grazed outside at night spent more time lying down when housed than those who were housed full-time, however, overnight, the opposite occurred. This is likely due to ewes outside preferring to graze rather than lie down, as they did not have the opportunity to graze during the day. Higher milk yields obtained from ewes in the hybrid system indicate that the nutrition of these ewes in mid-lactation was better than that offered to ewes in mid-lactation housed full-time.

Ewes in late-lactation housed during the day and grazed outside overnight spent only slightly less time lying down during the day compared with those grazed outside full time. Overnight, while both groups were outside, the full-grazed group spent more time lying down than those housed during the day, likely due to the latter group grazing rather than lying down, as they did not have the opportunity to graze during the day. The absence of a difference in milk yield between these groups indicates that different housing conditions in late lactation may result in different lying behaviour, but does not affect milk production.

Overall, the higher total daily lying times observed in both fully housed and fully grazed sheep compared with their hybrid counterparts indicates that a constant environment

results in sheep being more comfortable and relaxed in their surroundings. This may not, however, be beneficial to their milk production.

Ambient temperature of different housing systems

Sheep housed in a barn full-time spent more time lying down as maximum daily temperature increased. The maximum daily temperature in the barn was higher than that outside, however, lack of humidity data in each environment prevents further conclusions from being drawn as to why the differences in lying behaviour occurred.

BCS and live weight of sheep in different housing systems

Ewes in mid-lactation gained more BCS and live weight when managed in a barn during the day and grazed outside overnight compared with those housed in a barn full-time. This is likely due to ewes in the hybrid system grazing lucerne overnight, whereas fully-housed ewes energy intake was solely from TMR. This was also reflected in the higher milk yields from mid-lactation ewes in the hybrid system.

Ewes in late-lactation gained BCS and live weight when managed in a barn during the day and grazed pasture outside overnight, whereas those grazed full-time did not. This is likely due to the increased energy expenditure in the latter group by further daily walking distances to and from the milking parlour. As no difference in milk yield was observed between these groups, the extra energy intake presumably consumed by the hybrid group from TMR while housed during the day must have been used in gaining live weight.

3.2 Limitations

Several aspects of this study could be improved given the opportunity to do so. The majority of problems encountered during this trial were associated with technological difficulties. The first and most limiting factor of the trial was, however, due to the lack of replication of study groups, resulting in only observational results being presented. Replication of study groups would involve more space, labour, and money, which was not available for this trial. This is, therefore, considered a preliminary case study from which to base future research trials.

In-line milk metres did not record milk yield data for every sheep during every milking session, as seen by the lack of yield data points in Figure 2.3. Only three measurements were recorded prior to the beginning of the transition period, none within the transition period, and eleven from during the trial period. Furthermore, the trial began when sheep were already in at least mid-lactation, so the accurate prediction of whole lactation curves was not possible. Peak milk yield occurs in the first few weeks of lactation, and peak milk yield and lactation persistency would be important measurements to indicate what the most appropriate management systems to optimise milk production of EF dairy sheep in New Zealand would be. The limitations from the lack of milk yield data and the timing of the start of the trial prevented the knowledge gained from this trial from extending to what appropriate management of EF dairy sheep would be in early lactation in New Zealand.

The GPS collars used in this trial had high error margins, especially those inside the barn. The data obtained from GPS collars must, therefore, be viewed with caution. Also, the shortage of collars available meant that they could only be used to track the movements of sheep in the late-lactation group. While activity of the mid-lactation groups was estimated from the late-lactation data, these estimates cannot be validated.

As stated above, six temperature/humidity loggers were placed in the housing barn to record the temperature and humidity of each area of the barn every half hour for the duration of the trial, and data from the nearby weather station was to be used as the outside weather data source. Unfortunately, data was never able to be obtained from the weather station, so an online source was used. This provided the maximum air temperature in the Taupo region each day. Ambient temperature is only one of the factors contributing to the manifestation of heat stress in animals, other factors including humidity and wind speed, so this information is also required to determine how the environment is affecting animals. The time at which the maximum temperature occurred was not available from the outside weather source, so whether sheep in the hybrid systems were inside or outside at this time is unknown. For this reason, ambient temperature data could only be used to evaluate lying behaviour in the fully-housed and fully grazed sheep.

At the beginning of this trial, staff endeavoured to record health data weekly, however, due to time constraints, this was not possible. One day of health data was collected on the last day of the trial, including the presence and degree of dag staining, nasal and eye discharge,

evidence of orf, lameness, and udder health problems. As this was only recorded on the last day of the trial, it was not possible to determine the effect the housing systems had on different potential health problems.

A component of this trial involved comparing the different feeding systems. Nutrition is the major factor affecting ewe milk production, so the majority of milk yield difference is probably due to diet. This work is ongoing, and once complete, will provide a more complete picture of the optimal management system for EF ewes in New Zealand sheep dairy farms.

3.3 Implications and future research

A lot of information is still required to develop optimal farming systems for EF dairy sheep in New Zealand, and this study provides a basis for the development of future studies. While ongoing work is being completed regarding the feeding component of this study, future work on the welfare of sheep in different housing systems should be completed.

Future studies should include replicated groups in each management system to validate the significance of differences in results. It would also be advantageous to have sheep in their respective groups before lactation begins, so that milk yields can be measured from day one of lactation (depending on the lamb weaning system employed). In-line milk meters should also be checked and calibrated prior to the start of the trial to ensure yields are consistently measured for all sheep at all milkings. These improvements would result in the generation of accurate lactation curves of sheep in different housing systems that can be compared with each other.

The utilisation of GPS collars and accelerometers was useful to measure differences in animal behaviour between groups in different environments. In future studies, more accurate GPS technology should be used to reduce the error associated with results, and a higher number of both GPS collars and accelerometers should be used to justify the assumption of normality. This would also ensure that animals in all groups have their walking activity measured.

Along with ambient temperature, humidity in different environments should also be measured. Preferably, all aspects of weather, including air temperature, humidity, wind

speed, ground temperature, cloud, and level of solar radiation, should be measured at several time points throughout each day. This information can then be related to animal behaviour in the different environments, and daily milk yield. In the barn, temperature/humidity loggers should be placed evenly around the barn, unexposed to direct sunlight, to provide an overall picture of in-barn conditions. Health data should also be recorded at the beginning, during, and at the end of future studies to compare the incidence of health problems within each group.

This thesis showed that different management systems may affect sheep milk production in mid-lactation. Milk production is influenced by several factors, including dam genetics, age, parity, nutrition, body condition, stage of lactation, number of lambs, lamb weaning system, milking frequency, activity level, heat stress, mastitis, and the effect of housing on lactation. This thesis has provided a basis from which future trials can be based, highlighting the components influencing milk production that require further investigation in the New Zealand environment to develop a farming system that optimises sheep lactation performance. With the assistance of technologies such as GPS and accelerometers, animal behaviour can be observed to determine animal comfort in different environments, to ensure good welfare is maintained in these farming systems.

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