Biological efficiency, seasonality of feed demand, and economic optima within pastoral sheep production systems: A demand-driven linear programming model

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Peter L. Klaassen

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Models of pastoral livestock strategies are typically driven by feed-supply assumptions. An alternative approach is to focus on the requirements necessary to meet specific animal performance levels and the implications thereof for biological efficiency, feed demand seasonality, and systems economics relative to alternative feed supply functions.

A demand-driven deterministic steady-state enterprise level linear programming model of a self-contained breeding-finishing sheep meat livestock production system was developed in Microsoft Excel™ incorporating Solver™. For each week starting from ewe mating date, individual animal energy requirements (MJME) were simulated relative to specified performance levels. With the objective function being total carcass output and assuming a fixed but arbitrary system constraint of 10 million MJME, these simulation outputs were then brought together within a whole-of-system linear programming framework. Calculated outputs were animal numbers, flock structure, total meat carcass production and whole-of-system weekly feed requirements.

Relative to a baseline scenario developed from industry average animal-performance levels, model experimentation was undertaken to investigate how key livestock-production parameters impact on feed conversion efficiency (g carcass/MJME) and feed demand seasonality (MJME/week). Parameters were tested both one-at-a-time and in-combination.

In relation to feed conversion efficiency (FCE), parameters that reduced the maternal feed overhead cost per kg of production had the greatest effect with lamb-carcass weight and lambing percentage having the highest impact. Many system parameters had a curvilinear relationship to FCE with declining marginal returns. Effects were generally not additive with combined parameter effects either being less than additive or multiplicative. Overall system benefits tended to be lower than was superficially apparent from consideration of system components. Accordingly, major improvements require a focus on multiple system parameters.

In relation to feed-demand seasonality, several system parameters had large impacts. Through combined changes to system parameters, the feed-demand profile could be changed from almost flat to highly seasonal with high peak feed demands. Within a fixed feed constraint, it was also shown that changes to system parameters had a large impact on ewe numbers.

Although the main focus of this study was on FCE and feed demand seasonality, the base model was extended to incorporate the impact on economic returns. The purpose was primarily illustrative. With system feed demands still driven by assumed animal performance, in relation to a specified pastoral feed supply environment, initial feed deficits were calculated and then met, via transfer activities, by transferring feed from periods of excess to shortage at a pre-determined cost. Along with product pricing and animal production cost assumptions, system gross margin (GM) was then calculated per unit of system MJME.

Testing four system parameters for illustration, livestock parameters were shown to have very different relationships between FCE and GM return. Maximisation of biological efficiency will therefore not maximise economic efficiency and vice versa. In comparison to biological efficiency, which can be characterised by a smooth non-linear response curve, changes in a system parameter such as carcass weight can result in abrupt and step-wise responses to economic outcomes. Lastly, optimal systems were shown to be highly dependent on the specific feed-supply context.

Keywords: Sheep, livestock system, feed conversion efficiency, feed demand, gross margin, linear programming, lambing percentage, lamb growth rate, carcass weight, ewe size, hogget lambing, cull age, death rate, stocking rate.

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2-tooth ewe	Two-tooth ewe (one year old)
4-tooth ewe	Four-tooth ewe (two years old)
6-tooth ewe	Six-tooth ewe (three years old)
5yr, 6yr…10yr ewe	Five year old ewe, six year old ewe… ten year old ewe
ADG	Average daily liveweight gain
Cwt	Carcass weight
DM	Dry matter
DOM	Digestible organic matter
EBITR	Earnings before interest, tax, and rent
FCE	Feed conversion efficiency
FOB	Freight on board
Ha	Hectares
hd	Head (of livestock)
Hgt	Hogget
Kg	kilograms
LWG	Liveweight gain
Lwt	Liveweight
MA	'Mature aged', relating to the age of livestock and refers to ewes two years and older
MJME	Megajoules of metabolisable energy
M/D	MJME/kg DM

Chapter 1

Introduction

This introductory chapter has six parts. First, the contextual background to the research is described. Second is a description of the research problem. The third section describes the aims, objectives and research questions. The fourth section provides a brief description of the research methodology and outlines underlying philosophical perspectives. The fifth section provides an outline of the thesis structure and the final section provides a brief explanation of some of the terminology related to sheep production.

1.1 Research Background

1.1.1 New Zealand Pastoral Livestock Production

Compared to many other countries, New Zealand has a benign climate that allows for vegetative growth over much or all of the year (Metservice, 2008; Valentine & Kemp, 2007, p. 3). Able to be grazed *in situ,* New Zealand pastures can also provide cheap, high quality feed for livestock (Valentine & Kemp, 2007, p. 3). This, in combination with New Zealand's mountainous terrain and the land-use constraints imposed by the hilly contour, mean that agriculture production in New Zealand is derived mainly from livestock production systems based on grazed pasture (Bryant, 1990; Matthews, Hodgson, & White, 1999; Waghorn & Clark, 2004). For example, for the year ended 30th June 2014, pastoral exports represented 81% of total agricultural exports (Beef + Lamb New Zealand Economic Service, 2015a) and according to the 2012 Agricultural Census, grazing land (grassland, tussock and danthonia) accounted for 74% of the 14.4 million hectares of total New Zealand farm land (Statistics New Zealand, 2012).

1.1.2 The Sheep Meat Industry

The sheep meat industry is an important livestock industry in New Zealand. As at 30 June 2015, there were 28.6 million sheep in New Zealand (Beef + Lamb New Zealand Economic Service, 2015c) which, using data from the 2012 Agricultural Census, are run on 13,038 commercial sheep, and sheep and beef farms (Statistics New Zealand, 2012). Although wool remains significant, mutton and lamb contribute the majority of income. For the 2014-15 season, total lamb and mutton exports[1] were valued at $3.0 billion (FOB) (Beef + Lamb New Zealand Economic Service, 2016).

[1] Excluding co-products

Despite its importance to New Zealand, the sheep meat industry has been an industry under threat from competing land uses that offered better returns. For example, according to the Sheep and Beef Farm Survey, in the seven years from 2008/09 to 2014/15, the average profitability (EBITR) of sheep and beef farms in New Zealand was only $251 per hectare and the average return on farm capital was just 1.1% (Beef + Lamb New Zealand Economic Service, 2015b). In comparison, for owner-operators, the average dairy operating profit from dairy farms was $2,113 per hectare and the average return on assets was 5.0% over the same period (DairyNZ, 2015). This disparity in farm returns has resulted in many sheep farmers converting their farms to dairy production or to other higher value enterprises. As a consequence of this, there has been a steady decline in sheep numbers in New Zealand with total sheep numbers falling 50.6% from 1990 to 2015 (Beef + Lamb New Zealand Economic Service, 2015c).

1.1.3 Biological Efficiency

In animal production, biological efficiency or feed conversion efficiency describes the level of product output per unit of feed input (Large, 1970; Purchas, 2003, p. 8). Ensuring biologically efficient livestock production systems is important for a number of reasons.

1. Productivity and profitability

First, as outlined by McMeekan (1960) and Coop (1967), the biological efficiency of livestock systems is a key driver of total farm productivity. Productivity, defined here as the level of output per unit of land area, is important as this is a key driver of farm profit. For example, in response to the decline in sheep numbers in New Zealand, in 2011, Beef + Lamb New Zealand and the Meat Industry Association of New Zealand commissioned the Red Meat Sector Strategy Report to identify opportunities for improved industry profitability (Deloitte, 2011). Based on quintile analysis of the Beef + Lamb New Zealand Economic Service farm survey data, it was found that although the industry as a whole has low average profitability, some sheep farmers had very successful businesses with high profits. For example, Beef + Lamb New Zealand (2012) found that the top 20% (fifth quintile) of farmers have $950/ha higher profits in comparison to the bottom 20-40% (second quintile) of farmers . A key reason for this is the significantly higher levels of physical productivity on these farms (Table 1.1). For example, the kilograms of lamb meat sold per ha was 134% higher for the top 20% of farmers in comparison to the bottom 20-40% of farmers. In contrast, lamb price was not a major factor in higher farm profits being only 3% higher for the top farmers.

Although this analysis does not show whether the farmers in the top quintile are the same farmers each year, and also does not identify the physical and managerial causal factors, this does demonstrate the importance of physical output per ha in achieving high profits. The Red Meat Sector

Strategy Report therefore concluded that improving farm productivity represents a major opportunity for improved profitability within the red meat sector. To illustrate this, Deloitte (2011, p. 85) calculated that if those farms in the 50th, 60th and 70th percentiles were able to reach the level of productivity of farms in the 80th percentile, the sheep and beef sector would generate an extra $180 million dollars of profit per annum.

Table 1.1 Farm performance quintile analysis (Beef + Lamb New Zealand, 2012)

Farm Quintile (profit/ha)	Profit[1] ($/ha)	Lamb price ($/hd)	Lamb sales (kg/ha)	Lamb sales ($/ha)
20-40% (Q2)	-$300	91.70	44	222.20
40-60% (Q3)	$100	89.71	78	351.97
60-80% (Q4)	$300	90.66	83	377.08
Top 20% (Q5)	$650	94.23	103	522.01
Range (Q2 to Q5)[2]	$950	+3%	+134%	+135%

[1] EBITR

[2] Published data excludes quintile one (Q1)

2. Limited resources and the growing demand for food

In addition to economic reasons, the biological efficiency of food production is also important in terms of the ability to meet the growing global demand for food. For example, the United Nations projects that global population will increase from 7.2 billion in 2014 to 9.6 billion by 2050 (Gerland et al., 2014). This will cause a large increase in global food demands. To compound the problem, per capita consumption of livestock products such as meat is increasing (Delgado, 2003; FAO, 2011). It has been predicted that between 2002 and 2050, the annual per capita consumption of meat will increase 57% in developing countries, from 28 kg to 44 kg (Thornton, 2010). This increased demand for livestock products is driven primarily by increasing affluence, especially in Asia, and a move away from staples foods, such as rice, to western diets (Gerbens-Leenes, Nonhebel, & Krol, 2010; Pingali, 2006). In total, it is suggested that the world will need 50% to 100% more food by 2050 than in 2009 (Davies et al., 2009).

Although increased food production can be achieved through increasing the amount of resources used (land, labour, and capital), these resources are limited. In addition, resources for food production are coming under increasing pressure. One reason for this is due to the growing size of cities and the increased competition for land and water resources (Satterthwaite, McGranahan, & Tacoli, 2010). A second reason is due to governmental restrictions on deforestation as well as losses in agricultural land as a consequence of desertification, salinization, and soil erosion (Nellemann, 2009). Combined, these factors mean that increased food production cannot simply be achieved through increasing the amount of resources used, but must be achieved in part through increased production efficiency.

3. Environmental Sustainability

A third argument for improved biological efficiency is that efficient production is one of the key strategies to decrease the environmental impact of production (Gill, Smith, & Wilkinson, 2010). For example Cruickshank, Thomson, and Muir (2008) and Waghorn and Hegarty (2011) both concluded that increased efficiency of livestock production is one of the key ways to decrease the amount of methane production per unit of saleable product.

1.1.4 Farm Planning

Management is often regarded as the process of planning, implementation and control of activities (Gray, 2005, p. 43). The planning function of management is the process of choosing the sequence of actions that best meets the manager's goals. It involves the "contemplation of possible activities before a choice is made in the hope of ensuring a more acceptable result" (Dalton, 1982, p. 46). Once a plan is made then these plans can be implemented or actioned so that they can become a reality. After a plan is implemented then management can focus on the control function of management which is concerned with "measuring and correcting performance so that the outcomes specified in plans are achieved or the plans are revised as situations change" (Shadbolt & Bywater, 2005, p. 38). While the planning, implementation, and control functions of management are all important for effective management, the process of planning is the starting point.

Planning can be done at a strategic, tactical or at an operational level (Shadbolt & Bywater, 2005, p. 38). At the strategic level, farm planning focusses on achieving a sustainable long-term excellent fit for the farm business with its physical, social and financial environment. In the context of pastoral production, strategic planning is largely concerned with how to maximise and best match pasture growth to animal demand while at the same time ensuring sufficient income, maintaining or improving farm resources and improvements, and achieving personal and financial goals (Parker, Shadbolt, & Gray, 1997). In comparison, tactical planning focuses on within-year adjustments to a farm strategy. Operational planning focuses primarily on specific activities. For example, operational plans can include daily or paddock grazing plans which determine how long animals should be grazed in a particular paddock.

1.2 Research Problem

Information on how livestock production systems influence the biological efficiency of feed use (feed conversion efficiency) is important if farm productivity and profitability is to be maximised.

However, within the context of pastoral production, it is equally important to identify how the livestock production system affects the seasonal profile of feed demand. This is because, on pastoral farms, the variability of seasonal and annual pasture growth means that the amount and timing of feed demand often determines the feasibility of a particular livestock system. Understanding the profile of feed demand means that management can make decisions to manipulate feed supply to enable and ensure system feasibility. If it is impractical or too costly to manipulate feed supply, having an understanding of seasonal feed demands of different livestock systems will then allow management to choose a livestock system that matches feed supply better. Understanding how the livestock system impacts on total feed demand also means that managers can calculate the appropriate stocking rate for a given feed supply context.

While there have been many New Zealand and international studies that have evaluated the biological efficiency of alternative animal performance levels and alternative livestock strategies (for example Large (1970), Spedding, Walsingham, and Hoxey (1981), and Geenty (1995)), many of these studies have typically focused on a sub-system level of analysis and have ignored some important system interactions. Consequently, recommendations from these component studies do not readily translate into improved system performance (Checkland, 1981; McCall, Sheath, & Pleasants, 1994).

In contrast, whole-farm simulation and optimisation models capture systems interrelationships and incorporate the feedback effects inherent within livestock production systems. Examples of these models include Farmax (Bryant et al., 2010), Grazplan (Donnelly, Moore, & Freer, 1997; Freer, Moore, & Donnelly, 1997; Moore, Donnelly, & Freer, 1997), GrazMod (Johnson et al., 2008), LincFarm (Cacho, Finlayson, & Bywater, 1995; Finlayson, Cacho, & Bywater, 1995), APSIM (Keating et al., 2003), WFM (Beukes et al., 2008), MIDAS (Kingwell, 1986), IDEA (Doole, Romera, & Adler, 2012; Romera & Doole, 2015), and models developed by Ridler, Rendel, and Baker (2001), Cruickshank et al. (2008), Shadbolt (1982), McCall et al. (1999), and Ludemann (2009). However, the problem is that these models have typically been built in relation to a specified feed supply curve. The issue, then, is that the recommendations from these models do not apply to farms with a different feed supply situation. This is particularly important for New Zealand pastoral farms as feed supply varies from farm to farm and region to region (Valentine & Kemp, 2007, p. 3).

Consequently, in the context of sheep meat livestock production, a research gap is the lack of generic quantitative information on how key livestock parameters such as ewe lambing percentage, lamb growth rate, ewe size, target carcass weight, hogget lambing, age of ewe culling, and mortality rate impact on whole-of-system feed conversion efficiency. Therefore, from a decision making and strategic planning perspective within the context of pastoral agriculture, there is a need to develop a generic approach to assess the feed conversion efficiency of livestock production systems.

Also, although studies such as Cruickshank et al. (2008), Romera and Doole (2015), Ludemann (2009), and Large (1970) have expressly investigated how livestock strategies impact on system outputs (albeit through a supply-driven approach), little attention has been placed on quantitatively assessing how changes to livestock production systems influence feed demand seasonality. What is needed is an approach that measures both feed conversion efficiency and the timing of feed demand.

To assess these research gaps, for the purpose of strategic farm planning and within the context of pastoral production (and inherent variability in feed supply), an alternative approach is to reverse the traditional modelling method and start with animal feed demand.

Such an alternative approach has value where the focus, rather than being on feed supply, is on the requirement necessary to meet specific animal performance levels and the implications thereof for:

a.) Biological efficiency;
b.) Seasonality of feed demand; and
c.) Systems economics related to alternative feed supply functions and their associated costs.

This demand-driven approach is a change in paradigm in livestock modelling.

1.3 Research Aims, Objectives, and Research Questions

In respect to sheep livestock production systems, the overarching aim of this thesis is to quantify the relationships between biological production parameters and a.) biological efficiency, and b.) seasonality of feed demand. This aim was subsequently extended to developing a framework for assessing the effect on economic return through incorporation of seasonality components of feed cost.

While there are many parameters of the livestock system, key production parameters for self-contained sheep breeding and finishing systems include ewe lambing percentage (% lambs tailed per ewe mated), pre-weaning and post-weaning lamb liveweight gain (g/day), ewe size (kg), hogget lambing (% hogget lambs tailed relative to total hoggets at mating date), lamb carcass weight (kg), cull age (years), and ewe mortality rate (% per annum). Although the choice if these parameters was judgmental, the selection of included parameters has been made in reference to the focus of prior research (Cruickshank et al., 2008; Geenty, 1995; Harrison et al., 2014; Large, 1970, 1976; Ludemann, 2009; McGregor, 1979; Rutherford, Nicol, & Logan, 2003; Shadbolt, 1982; Wallace, 1953). In respect to these key production parameters, specific objectives of this research are:

a. To develop a model capable of quantifying both the feed conversion efficiency of the sheep livestock system as measured by grams of meat carcass per MJME of total annual system feed demand, and also the seasonality of system feed demand measured as the percentage of annual feed demand (MJME) that is required each week starting from ewe mating date.

b. To use this model to assess relationships between production parameters and overall system outputs.
c. To extend the model to incorporate seasonal cost elements of feed supply.
d. To develop generic systems-level planning heuristics for managers of pastoral sheep farms

From the aims and objectives of this research, there are four major research questions:

1. How do key production parameters of the sheep livestock system impact on whole-of-system feed conversion efficiency?

2. What is the impact of increasing system production parameters on the seasonality of whole-of-system feed demand?

3. For total system feed demand to remain unchanged, how do key livestock production parameters impact on the number of breeding ewes able to be farmed?

4. Do livestock production parameters that increase biological efficiency also increase economic returns?

1.4 Research Methodology

In respect to the traditional classification of scientific enquiry, this research can be regarded as quantitative. However, in contrast to the scientific method of the natural sciences, this research does not aim to test theory and does not begin by the statement of a hypothesis. Rather, the approach used in this research falls within the field of Management Science (also known as Operations Research) and follows the problem solving process and is based on systems-thinking using systems models (Anderson, Sweeney, & Williams, 2000, p. 2; Daellenbach & McNickle, 2005, p. 579; Ragsdale, 1995, p. 8). The management science approach follows a well-defined process. The first stage in this process is to identify and formulate the problem. This includes gathering all the relevant data. The next step is to construct a scientific (typically mathematical) model that “attempts to abstract the essence of the real problem” (Hillier & Lieberman, 2005, p. 2). The model is then analysed and the results tested. Next, suitable experiments are conducted to test the sensitivity of parameters within the model. This processes helps validate the model and gives confidence that the model is a sufficiently precise representation of the essential features of the situation that is being analysed and that the conclusions (solutions) obtained from the model are also valid for the real problem. If needed, the model is then modified and the outputs recalculated. The final step is the implementation of model findings.

In relation to the modelling approach that is used, this research is normative and the model's predicted outcomes is at the level of the system and is based on specified and interacting variables. As such, findings are not tested for statistical significance.

A defining philosophical perspective of management science and of this research is that of systems-thinking. This refers to a way of thinking that deliberately considers the relationships of parts to one another and recognises that, when new components are added to the system, a new dynamic is created that is likely to alter overall system performance (Shadbolt & Bywater, 2005, p. 31). In contrast, a reductionist approach implicitly assumes that "explaining the behaviour of parts of the greater system and then aggregating these partial explanations is sufficient to allow us to understand and explain the behaviour of the system as a whole" (Daellenbach & McNickle, 2005, p. 17). This approach, however, does not account for the interactions within systems and may therefore lead to significant biases in decision-making (Nuthall, 2010, p. 141). Alternatively, it could be argued that the reductionist approach simply focuses on components and ignores the greater system without any assumptions as to the overall system behaviour.

To avoid confusion, it is worthwhile emphasising here that while this research explicitly uses a system-thinking approach, systems boundaries are drawn in relation to the problem being investigated. As this research primarily focuses at the level of the livestock system, systems interactions are therefore limited to the level of the livestock system and not the farm system.

1.5 Outline of the Thesis

Following this introductory chapter, there are eight further chapters to this thesis.

The purpose of Chapter 2 is to discuss how the biological efficiency of livestock production systems are analysed within the context of pastoral production. The issues that are addressed in this chapter include the appropriateness of different measures of biological efficiency, the levels at which biological efficiency can be measured (e.g. component or systems-level analysis) and the use of modelling for the calculation of biological efficiency. Different modelling techniques are described, with linear programming in particular being described in detail. This chapter also describes different models of livestock systems and discusses the strengths and weaknesses of these models for the purpose of planning efficient and feasible livestock systems. At the conclusion of the chapter, it is argued that, for the purpose of strategic analysis, an alternative approach to the traditional livestock modelling methodology is to develop a demand-driven model that is capable of showing how changes to the livestock system will influence both feed conversion efficiency and the seasonality of feed demand.

The focus of this research is on sheep meat production systems. Accordingly, the purpose of Chapter 3 is to identify key parameters of the sheep livestock system and to discuss how different livestock systems may impact on both feed conversion efficiency and the seasonality of feed demand. This leads to the identification of the gap in knowledge which then forms the basis of the research questions that will be answered in this study.

The purpose of Chapter 4 is to describe the specific linear programming technique that was used to develop the biological livestock model and to outline the assumptions and parameter values used in the baseline scenarios.

In Chapter 5, the results of the baseline model are presented. This chapter also discusses model verification and validity.

In Chapter 6, the results of one-at-a-time experimentation of key parameters of the sheep livestock system are presented. This chapter shows how, if other factors remain constant, lambing percentage, pre-weaning and post-weaning lamb growth rate, ewe size, target carcass weight, hogget lambing, age of ewe culling, and mortality rate impact individually on meat output, feed conversion efficiency, ewe numbers and the seasonality of feed demand. This chapter also discusses research findings and explains how the results compare to the literature.

In Chapter 7, the effect of simultaneous changes in livestock parameters are explored. Due to the number of possible scenarios, experimentation focuses on testing the combined effect of related parameters and using insights that arose from one-at-a-time experimentation.

The purpose of Chapter 8 is to provide a framework for placing biological efficiency within an economic context. Whereas biological efficiency can be evaluated within a generic framework which applies across a broad range of contexts, economic efficiency requires acknowledgement of the specific contextual conditions relating to the seasonal cost of feed and seasonality of product prices, both of which will vary depending on location and year. This chapter demonstrates the development of the model to calculate key metrics for enterprise gross margin returns in response to various physical performance levels. The specific contextual situations presented in this chapter are illustrative for the purpose of demonstrating the capacity and flexibility of the model. The application of this model to diverse New Zealand and international contexts lies beyond the bounds of this thesis.

The final chapter provides a review and synthesis of previous chapters. Issues that are addressed include the use of linear programming as a framework to investigate the biological efficiency of livestock production systems, limitations of the model, and future research. The thesis concludes with a restatement of the major research questions and a summary of the findings.

1.6 Terminology

Age and sex terminology of sheep is complex. Adult female sheep are referred to as ewes and adult male sheep are referred to as rams. Young sheep under 12 months of age are referred to as lambs. However, in farmer terminology, lambs are referred to as hoggets from about six months of age to the eruption of their first incisor teeth at about one year of age. From this age onwards, age terminology relates to the number of incisor teeth. Two-tooth ewes (2-tooth) refers to ewes which have one pair of incisor teeth which erupt at about one year of age. In most sheep, another set of incisor teeth erupt every year. Therefore, four-tooth ewes refer to ewes two years of age while six-tooth and eight-tooth ewes refer to ewes that are three and four years old respectively. The normal number of incisor teeth are four pairs and therefore, eight-tooth ewes are also referred to as full mouth ewes. From this age, ewes are referred to by their age in years. For example, five-year ewes are ewes that are five years old and six-year and seven-year ewes are ewes that are six and seven years of age respectively. The terms “mixed-aged ewe” or “mature-aged ewe” are often used interchangeably and describe a flock or mob of ewes which are of different ages but are older than two years of age. As both these terms can be described this way, to avoid ambiguity, in this thesis, the abbreviation “MA” refers to the term “mature-aged” ewe.

In relation to age terminology, a common confusion is that farmers also refer to ewes by their expected economic life expectancy. This is particularly the case when purchasing older ewes for breeding. For example, a one-year ewe can refer to old cull ewes that are purchased with the expectation that they will be keep for one more year prior to being slaughtered. Two-year ewes are ewes that are purchased with the expectation that they will be kept for two extra years prior to being sold.

In addition to describing the age of the animal, the term “lamb” is also used to describe the meat from lambs. The term “mutton” is used to describe meat from older sheep. When describing a lamb of a particular sex, the term “ewe lamb” refers to a female lamb and the term “ram lamb” refers to a male lamb. As a further point of confusion, lambs are often categorised by the age of their dam. Consequently, a description of a particular lamb of a specific birth rank and sex is often preceded by a description of dam age. For example, a “MA ewe single ram lamb” describes a male lamb born from a single litter by a MA ewe, while a “hogget twin ewe lamb” refers to a female lamb born from a twin litter by a hogget.

In this research, the terms growth rate and liveweight gain are used interchangeably when referring to the growth of animals.

All prices are in New Zealand dollars unless indicated otherwise.

Chapter 2

Biological Efficiency within Pastoral Livestock Production Systems

2.1 Introduction

The biological efficiency of livestock production systems is an important component of farm productivity and profit. The purpose of this chapter is to explain the concepts of efficiency and systems and to relate these concepts to biological efficiency analyses of pastoral livestock production systems. Issues that are addressed in this chapter include the appropriateness of different measures of biological efficiency, the levels at which biological efficiency can be measured (e.g. component level or systems-level analysis), and the different methods that can be used. Following a discussion on the New Zealand pastoral feed supply context, this chapter also specifically discusses the use of models to analyse the biological efficiency of livestock production systems and the issue of simple versus complex models. In the context of seasonal pastoral production systems, this chapter concludes with a theoretical argument for the development of demand-driven enterprise level models of livestock systems that provide generic planning information by showing how livestock systems impact on both feed conversion efficiency and the seasonality of feed demand.

2.2 Efficiency

Efficiency is a measure of how well resources are used in a given activity (Daellenbach & McNickle, 2005, p. 13). While this idea is widely used, the physical and biological sciences define the concept of efficiency differently in comparison to economics.

In the physical and biological sciences, efficiency is usually defined as the ratio of output to input over a specified period of time (Spedding et al., 1981, p. 3; Tow, Cooper, Partridge, & Birch, 2011). Although physicists and engineers, who have employed the concept for much longer, have adopted the Greek "η", (reserving "e" for energy), biologists have tended to use the letter "E" to denote efficiency (Large, 1970; Spedding et al., 1981, p. 3). An expression of efficiency will therefore take the form $E = O/I$, where E is the efficiency, O is the output and I is the input. Efficiency will be improved if greater output is achieved for the same level of input or if less input is required to achieve the same level of output. Conversely, efficiency will be reduced if there is less output for the same level of input or if more input is required for the same level of output.

Familiar examples of everyday usage of efficiency or ratios of output and input include "kilometres per litre", "words per minute", and "kilometres per hour". As these examples suggest, ratios of output and input can apply to innumerable combinations of output and input and each of these can be expressed in many different terms (Spedding et al., 1981, p. 3). The choice of outputs and inputs and the choice of the units in which they are expressed must therefore be based on the reasons for the calculation (Spedding, 1976). There is no essential difference in applying the concept of efficiency to specific applications. For example, energetic efficiency is a measure of efficiency that relates to energy output and energy input (Spedding et al., 1981, p. 3). Biological efficiency, the topic of this research, is described in the next section.

In economics, efficiency can relate to a number of different concepts. Three key efficiency concepts are the economic optimum, productive efficiency, and technical efficiency. First, rather than relating to a ratio of output to input, economic efficiency refers to the notion of an economic optimum (Doll & Orazem, 1984, p. 61). This is the point where marginal revenue is equal to marginal cost (or when the first derivative of the profit function is zero). For individual firms, economic efficiency is therefore concerned with maximising the difference between revenue and total costs (Daellenbach & McNickle, 2005, p. 13). In relation to markets or economies as a whole, the term allocative efficiency is used to describe the point at which the production of goods reaches the economic optimum (Henderson & Poole, 1991, p. 291). In contrast to the concept of an economic optimum, productive efficiency refers to the ratio of output value to cost (Tow et al., 2011, p. 33). This can be achieved by minimising costs for a given level of output or maximising output for a given level of costs.

Using the precise terminology of the discipline of economics, technical efficiency is the term used to describe the effectiveness in which a given input is used to produce a given output (Coelli, Rao, O'Donnell, & Battese, 2005). Most commonly used in the branch of applied economics, this concept of efficiency is expressed using input-output ratios. Therefore, while called by a different name, this is the concept of efficiency that is most often used in the biological sciences.

2.3 Biological Efficiency

Biological efficiency is defined by Spedding et al. (1981, p. 4) as the efficiency of a biological process or processes and can be considered over a wide range of levels of organisation, from the level of specific biochemical processes within tissues of plants and animals to biological processes at the level of the individual or whole populations. Spedding (1973) therefore explains that while the *meaning* of biological efficiency may remain constant, its *expression* must vary widely depending on the point of view and the level of analysis.

Although an expression of biological efficiency involves a biological process, it can be expressed in either biological or non-biological terms. Non-biological terms used to describe biological efficiency include physical or even financial or economic measures. For example, the biological efficiency of meat production can be expressed in terms of the kilograms of meat produced per unit of feed input or in terms of the dollars of meat sold per unit of feed input. While it is a more accurate use of words, the reason that the expression of biological efficiency is not restricted to biological terms is because “within any applied interest, such as agriculture, economic assessments are of major importance, not only in their own right, but as a means of determining the relative importance of component biological processes” (Spedding, 1973, p. 14). However, a problem of using economic terms to express the efficiency of biological processes is that economic factors often go beyond the biology of the processes being measured. Economic measures, therefore, cannot by themselves confer understanding of the biological processes on which the economic output depends. Consequently, if the purpose is to understand the underlying biological processes, it is preferable to express biological efficiency using biological terms.

2.4 Livestock Production

While there are other purposes for keeping animals, the major purpose of livestock production is to convert plant feed into animal products (Purchas, 2003, p. 4; Stevens, 1958, p. 1). Accordingly, Fraser and Stamp (1957, p. vi) refer to sheep as “metabolic machines”. However, unlike in manufacturing where products are assembled, in agricultural production, products are grown using biological processes and production cycles and are then harvested (Woodford, 2014). Another important characteristic of animal production is that production outputs (i.e. the animal) can also be capital (Jarvis, 1974). For example, while male and female lambs may be slaughtered for meat, they may also be kept as breeding animals. Although short term production output increases as more animals are slaughtered, future production will be compromised unless a proportion of the total population is retained for breeding purposes. Conversely, increasing production capacity requires a greater number of animals to be retained for breeding stock. This reduces the number of animals that can be sold and therefore reduces short term production output. As these examples show, ongoing or sustainable animal production is therefore characterised by an animal system comprised of different stock categories including breeding male and female animals as well as young stock that are either retained as replacements to the breeding flock or are sold. For ruminant production systems, such as sheep and cattle production systems, the fact that production outputs can also be capital goods is of particular relevance as these livestock systems are characterised by low reproductive rates.

There are many different outputs from livestock systems. For example, common sheep products are listed by Purchas (2003, p. 4) and include meat; wool; live animals for local sale (store animals) and for export; skins and leather and wool products from them; abattoir products such as tallow, gelatine, and pharmaceuticals; wool grease and its pharmaceutical and cosmetic derivatives; milk and its derivatives; and fertiliser derived from bodies, dung and dags. In addition to products that can be sold, negative by-products can also be considered outputs. For example, Cruickshank et al. (2008)

measure methane production as an output of the sheep livestock production system. However, meat production is a key output of livestock systems and is the focus of this research.

2.5 Systems Theory

Production from livestock requires a livestock system. There are several important theoretical aspects to the concept 'system'. First, systems are "sets or groups of components that interact to perform a function" (Shadbolt & Bywater, 2005, p. 30). For example, the livestock production system requires a group of interacting animals and management activities which enable the conversion of plant feed into animal products such as meat.

A second defining characteristic of the concept 'system' is that "the whole is greater than the sum of its parts" (Daellenbach & McNickle, 2005, p. 39). In other words, a system exhibits behaviours or properties that none of its components individually may exhibit, i.e. a system has 'emergent properties' (Checkland & Scholes, 1990). In livestock production, meat is not a sum of the biological processes that are operating, but rather, a product of them.

Another important characteristic of a system is that it has a boundary. For example, to describe a system, it is necessary to identify what is in the system and what is outside the system. However, a challenge is that, in reality, there are no clear divisions between one system and the next. For example, livestock production is not an independent system but forms a subsystem within the greater farming system, which is in turn part of a food system and an ecological system and a socio-economic and political system. As a result, Daellenbach and McNickle (2005, p. 81) argue that systems are not "out there" but are abstract mental constructs or personal conceptualizations. This is because system descriptions are based on arbitrary divisions which do not exist in nature. Consequently, the definition of a system is therefore, to some extent, subjective and should be based on the purpose of describing a particular system (Daellenbach & McNickle, 2005, p. 81).

In this research, the focus is on the biological efficiency of particular livestock production systems. As a result, the systems boundary is drawn around the livestock system which therefore forms the "narrow system of interest" (Daellenbach & McNickle, 2005, p. 589). The farm, food, ecological and other wider systems thus form the "wider system of interest" that controls the resources and provides the control inputs for the livestock system.

2.6 Feed Conversion Efficiency of Livestock Production

The biological efficiency of the livestock production system can be measured in many different ways depending on the purposes of the calculation (Spedding, 1976). However, assuming the purpose of livestock production is to produce animal products from plant feed, the biological efficiency of the livestock production system can be measured as the level of product output per unit of feed input (Large, 1970; Morris, Brookes, Parker, & McCutcheon, 1994; Purchas, 2003, p. 8). As this measure of biological efficiency relates to the efficiency of feed conversion, the term "feed conversion efficiency" is often used (Kerr, 2010; Spedding, 1976, p. 36; Wallace, 1955). As such, the letters "FCE" can be used to denote the biological efficiency of livestock production.

There are many different metrics that can be used to measure the relationship between product output and feed input (Spedding, 1976, p. 29; Waghorn & Hegarty, 2011). This is due to the number of ways product output and feed input can be measured and expressed.

2.6.1 Product Output

In livestock production, the measure of output depends on what is being produced and on the focus or purpose of the analysis. For most livestock systems, product output is measured as the amount of product sold and is measured in the same way as farmers are paid. For example, meat production can be measured as the kg of meat carcass sold, milk production can be measured as the kg of milk-solids sold and wool production can be measured as the kg of greasy wool sold. As these examples show, product output is most often expressed in kilograms.

In measuring the biological efficiency of livestock production, a challenge is that there are multiple outputs. For example, sheep produce both meat and wool. Dairy production systems produce milk but they also produce meat from cull cows.

When the combined output of multiple products are being analysed, expressing total output in physical terms does not account for the relative importance of different outputs. For example, while the output of meat and wool can both be expressed in kg, the value of each of these products are often much different. For this reason, an economic rather than a physical measure of output is often used when comparing the combined production of a number of different products.

2.6.2 Feed Input

To calculate the feed conversion efficiency of livestock production, feed input can be measured either as the weight of feed (e.g. kg DM) or as the nutritive value. For pastoral production systems, feed input is commonly measured in terms of energy. This is because energy is often the most limiting nutrient (Nicol & Brookes, 2007; Smeaton, 2007; Sykes, 1980).

In describing the energy value of feed, an important factor to consider is that not all of the total or gross energy (GE) in the feed is available to the animal. Of the feed that is eaten, a proportion of feed energy is wasted in the faeces, urine and fermentation gases such as methane (McDonald et al., 2011, p. 258; SCA, 1990; Waghorn, Burke, & Kolver, 2007). As a result of these loses, GE does not provide a clear indication of true feed value. The energy value of a feed and an animal's feed requirement are therefore primarily described in relation to metabolisable energy (Freer, Dove, & Nolan, 2007, p. 1; Nicol & Brookes, 2007; Sykes, 1980; Waghorn et al., 2007). This is the proportion of total feed energy that can be absorbed from the digestive tract and retained for the metabolic processes of the animal such as maintenance and growth. While other measures of feed energy are also used, metabolisable energy has been adopted as the standard measurement of feed energy in New Zealand, Australia and the United Kingdom and is expressed in mega joules (e.g. MJ ME). In America and Canada, metabolisable energy is expressed in mega calories (Naazie, Makarechian, & Hudson, 1997).

Another factor to consider when describing feed input is whether to calculate feed input based on the amount of feed that is grown or supplied by the farm, or on the amount of feed that is utilised or eaten by the animal. For example, farm experiments that report actual farm performance often measure feed input as the amount of feed grown. In comparison, predictions of feed energy demand are usually calculated at the level of the animal and therefore relate to the amount of feed eaten (Nicol & Brookes, 2007). Because a proportion of feed that is supplied is not utilised by the animal as a result of wastage (i.e. through trampling of pastures), measuring feed input as the amount of feed grown will result in lower efficiency ratios in comparison to when feed input is measured as the amount of feed eaten. To avoid confusion, the term 'utilisation efficiency' (Coop, 1967) should be used when feed input is measured as the amount of feed that is grown or supplied while the term 'feed conversion efficiency' should be reserved for when feed input is measured as the amount of feed eaten or required by the animal. Ultimately, the decision on how feed input is to be defined should be consistent with the level of analysis and the defined system boundary being studied, which in turn, depends on purpose.

2.6.3 Time

Although this is often implicit in the calculation, measures of biological efficiency will always relate to a specific time period. In livestock production, the unit of time is based on the production cycle of breeding females, which for sheep and cattle is normally measured as one year.

2.6.4 Individual and System Measures of Efficiency

When analysing the feed conversion efficiency of livestock production systems, a further factor to consider is the level at which product output and feed input are measured. For example feed conversion efficiency can either be calculated at the level of the individual animal or at the level of the production system as a whole.

Efficiency values for output of carcass in relation to feed dry matter intake by meat-producing animals is shown in Table 2.1. The measure of efficiency that is used is the kg of meat carcass for one animal per unit of feed intake (Kg DM). However, the amount of feed energy required is calculated for that one animal based on the feed requirements after that animal is weaned. The problem of measuring the efficiency of production in this way is that it excludes the overhead feed costs of maintaining the breeding flock and therefore is generally higher than that of the whole system in which it is part (Spedding, 1976). Therefore, when analysing the livestock system as a whole it is important to use system-level measures of biological efficiency. This can be done by measuring feed input as the feed required by all animals within the system.

Table 2.1 Efficiency values for output of carcass in relation to post weaning feed dry matter intake by meat-producing animals (Spedding et al., 1981, p. 253)

	Feed intake of individual[a] (kg DM)	Carcass output (kg)	E[b]
Cattle	3005	257	8.6
Sheep	108-136	19-18	17.6-13.2
Pigs			
(pork)	93.6	44.8	47.9
(bacon)	174.8	67.3	38.5
Rabbits	2.37	0.99	42.00
Hens			
(broilers)	4.0	1.45	36.0

[a] Other than milk

[b] $E = \frac{\text{Carcass output (kg)}}{\text{Feed intake (kg DM)}} \times 100$

2.7 Purpose of Calculating Efficiency

Spedding et al. (1981, p. 11) explain that there are two main reasons for calculating efficiency. The first reason is to decide which process or system is more (or most) efficient at doing a specified thing in a specific context. The object is to make it possible to choose the most efficient of those considered. The second purpose is to assess efficiency in such a way that it can be improved if it is not satisfactory. “A simple ratio does not allow this” (Spedding et al., 1981, p. 11).

There are two important conclusions to be drawn from these considerations. First, a calculation of efficiency is a static summary of system performance and a single figure for the efficiency of a system can only apply to a highly specific situation (Spedding et al., 1981, p. 11). Second, “if efficiency calculations are to be used as a basis for change and improvement, the process or system has to be described in sufficient detail and in such a way that its sensitivity to change in important variables can be adequately expressed" (Spedding et al., 1981, p. 11). Because the livestock system is a complex system with many important interactions between system components, this requires the use of dynamic systems models.

Models and the benefit of modelling are discussed in section 2.9. However, before an analysis of different livestock models can be made, it is important to consider the pastoral production context. In particular, it is important to consider the inherent seasonality of feed supply and the subsequent need to match animal requirements to feed supply. This is discussed in the following section.

2.8 The Pastoral Context: Feed Supply and Demand Seasonality

A fundamental characteristic of pastoral livestock production is inherent seasonality of feed supply (McMeekan, 1960, p. 219). For example, although New Zealand has a benign climate that allows for vegetative growth over much or all of the year, pasture growth rates vary considerably over an annual period (Baars, Radcliffe, & Rollo, 1990). Valentine and Kemp (2007) show pasture growth rates for six different regions in New Zealand (Figure 2.1).The large degree of seasonal and annual variation in pasture growth is the result of differences in temperature, water availability, soil, and topography (McKenzie, Kemp, Moot, Matthew, & Lucas, 1999). The effect of dry summers is apparent in Figures 2.1b and 2.1c, while the effect of low winter temperatures is apparent in Figure 2.1b, 2.1c, 2.1e and 2.1f.

To help reduce the seasonality of feed supply and ensure sufficient feed is available to meet animal demands, there are a number of strategies that can be implemented by management. First, managers can manipulate feed supply by controlling the utilisation of pasture by implementing different grazing methods (Matthews, Hodgson, et al., 1999). For example, paddock subdivision combined with rotational grazing allows autumn pasture to be saved for use during winter. Feed supply can also be manipulated by conserving pasture as hay, balage or silage during periods of feed surplus and by feeding out during times of feed deficit (White, Matthew, & Kemp, 1999). Feed supply can also be improved by improving pasture growth rates through improved pasture species, improving soil fertility and by irrigation (Kemp, Condron, & Matthew, 1999; Kemp, Matthew, & Lucas, 1999; McLaren & Cameron, 1996). The profile of feed supply can be further altered through supplementary crop production and through the feeding of concentrate feeds purchased from off-farm (Valentine & Kemp, 2007).

However, despite these strategies, for many farms, there are limits to which feed supply can be manipulated without significant cost. For example, transferring feed through saved pasture causes feed losses due to the senescence and decay of pasture and a reduction in feed quality (Matthews, Harrington, & Hampton, 1999; Valentine & Kemp, 2007). Manipulating feed supply through feed conservation, growing supplementary crops, and through irrigation, fertilisers, and improved pasture species is also expensive and often impractical on many hill country farms (Valentine & Kemp, 2007). Therefore, unlike in-door grain feed livestock production systems, feed supply in pastoral livestock systems can be considered "inelastic" and is characterised by considerable seasonal variation (McMeekan, 1960, p. 219).

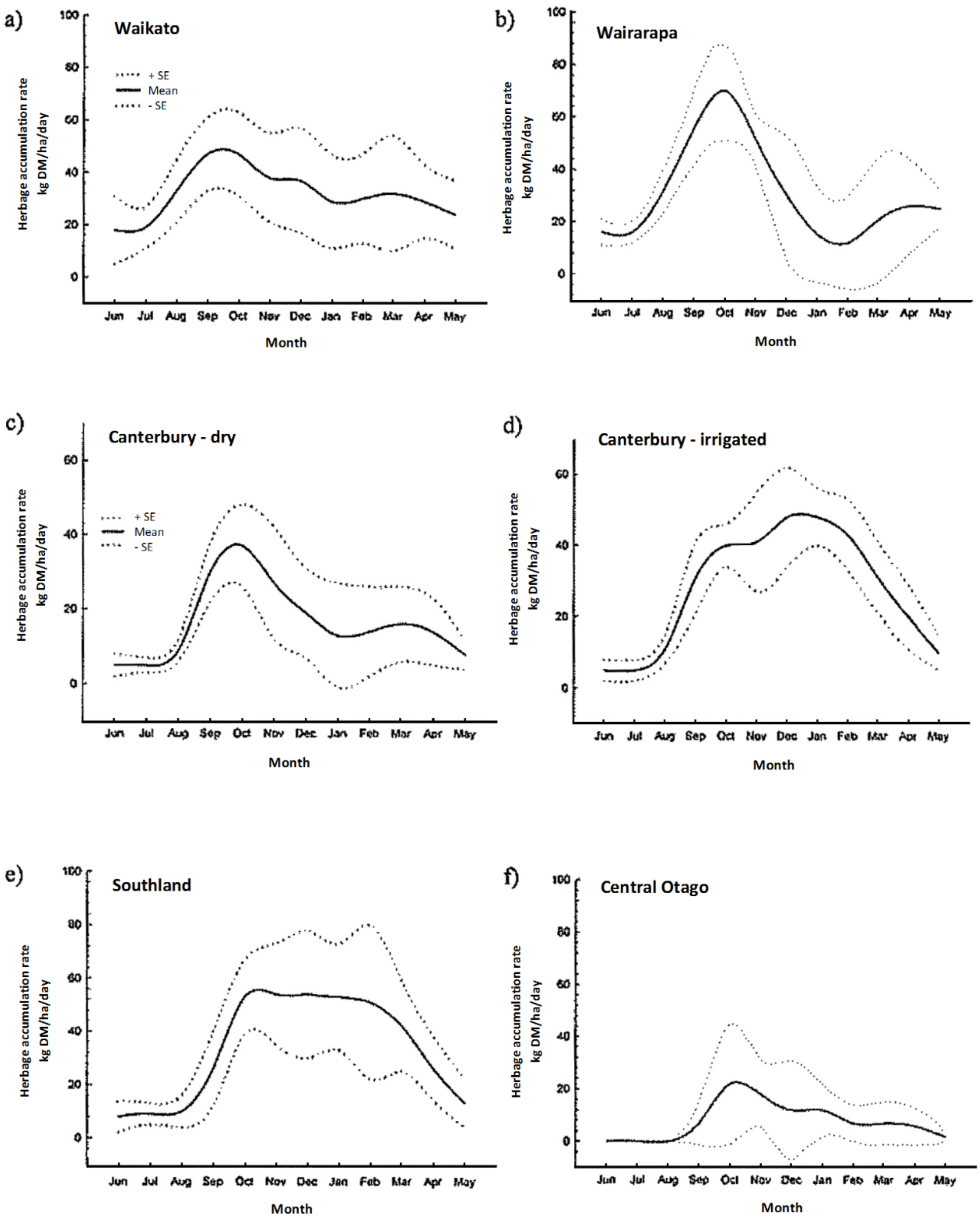


Figure 2.1 **Seasonal pasture growth rates (kg DM/ha) in a) Waikato, b) Wairarapa, c) Canterbury dryland, d) Canterbury irrigated, e) Southland and f) Central Otago (Valentine & Kemp, 2007, p. 5)**

As a consequence of the seasonality of feed supply inherent in pastoral production, a fundamental challenge of pastoral livestock farming is to match feed demand with supply (Nicol, 1996). This is because matching feed supply and demand is the key factor that determines system feasibility (Bryant, 1990; Matthews, Harrington, et al., 1999; Valentine & Kemp, 2007). For example, if feed supply is less then feed demand then animal performance will suffer and desired production levels will not be reached. As a result, Parker et al. (1997) argue that in the context of pastoral production, strategic planning should focus on developing plans that maximise and best match animal demand with pasture growth. The importance of matching feed supply and demand is also stated by Sheath, Hay, and Giles (1987) who argue that matching feed supply and demand as closely as possible is one of the five important rules of [farm] management.

The need to match feed supply and demand means that livestock strategies aimed at increasing biological efficiency must, prior to being implemented, be analysed for their potential impact on the seasonality of feed demand. For example, if there is a mismatch between feed supply and demand, understanding the profile of feed demand allows management to make decisions to manipulate feed supply in order to match with the new feed demand requirements and therefore enable farm system feasibility. If strategies to alter feed supply are impractical or too costly, it will allow management to choose a livestock system that matches feed supply better. Information on animal feed demands therefore enables livestock farmers to plan their feeding strategies (Nicol & Brookes, 2007, p. 151).

2.9 Models and Modelling

Models represent real objects or situations, for a particular purpose, in a simplified abstract form (Anderson et al., 2000, p. 6; Kelly & Bywater, 2005). Models can be categorised into three distinct types: Iconic, analogue, and symbolic.

Iconic models are "reproductions of physical objects, usually to a different scale and with less detail" (Daellenbach & McNickle, 2005, p. 81). An example of an iconic model that is given by Dent, Harrison, and Woodford (1986, p. 9) is a small scale farmlet which can be used to investigate different farming techniques. Another example of an iconic model is a scale model of a ship which can be used by engineers to test the hydrodynamic properties of the hull design prior to construction of the real ship.

In contrast to iconic models, analogue models represent the real object being modelled not just by miniaturisation, but by using substitutes for essential properties or features of the system (Daellenbach & McNickle, 2005, p. 81). A farm map is an example of an analogue model where features such as fences, shelterbelts and farm buildings are represented by drawing lines and icons on paper.

A symbolic model is a model that represents the relationships between system components by means of symbols, logic functions and mathematical expressions (Daellenbach & McNickle, 2005, p. 589). These models are often just referred to as mathematical models (Anderson et al., 2000, p. 7) and are the most useful type of model for planning farm systems.

2.9.1 The Advantage of Mathematical Models

Analysing a problem using a mathematical model has several advantages. First, models are simplified versions of reality (Ragsdale, 1995, p. 4). Therefore, experimenting with mathematical models is substantially less costly, in both time and money, than experimenting with the real object or situation. For example, Daellenbach and McNickle (2005, p. 139) explain that "mathematical models are a practical way to obtain answers to problems quickly and reasonably inexpensively".

Second, mathematical models are often much easier to manipulate and, in contrast to real-life experiments, a new or updated answer can often be found within a few seconds of computer time (Daellenbach & McNickle, 2005, p. 139). Models also have an advantage because they reduce the risks associated with experimenting with the real situation (Anderson et al., 2000, p. 7). For example, testing with models mean that bad decisions can be avoided.

Third, models allow us to gain insight and understanding about the object or decision problem under investigation (Ragsdale, 1995, p. 4). As noted by Hillier and Lieberman (2005, p. 12), "models are invaluable for abstracting the essence of the subject of inquiry, showing interrelationships and facilitating analysis".

Lastly, mathematical models allow for the objective analysis of systems interactions (McCall et al., 1994). This is particularly important when investigating complex problems where important interactions between system components occur.

2.9.2 Simple versus Accurate Models

When describing models it is important to remember that the ultimate purpose of models is to aid decision making. Therefore, Hardaker, Pandey, and Patten (1991, p. 10) argue that, in modelling, "the focus should be on representing the essential features of the system rather than on the impossible task of reflecting all the detail and complexity of the real system". This is in agreement with House and McLeod (1977) who strongly argue that perfectly accurate models are an unrealizable, ideal concept that implies a model is an exact duplicate of the real system. Accordingly, House and McLeod (1977) reject the desirability of perfect models, even as an ideal concept, on the grounds that understanding them would be as difficult as understanding the real system. This view is also consistent with that of Herbert Simon who said that "mathematical models do not have to be exact, they just have to be close enough to provide better results than can be obtained by common sense" (Anderson et al., 2000, p. 7). Rather than trying to model reality as accurately as possible, Anderson et al. (2000, p. 12) also note that simpler and more easily understood models are often preferred despite the recommended solution being only a rough approximation of the best decision. The focus, therefore, should be on developing models that provide adequate decision heuristics. Evidence for this is given by Gigerenzer and Selten (2002), who, after analysing simple alternatives to full rational analysis as a mechanism for decision making, propose that simple heuristics frequently lead to better decisions than the theoretically optimal procedure. As Ragsdale (1995, p. 87) explains, a heuristic is a rule-of-thumb for making decisions that might work well in some instances, but is not guaranteed to produce optimal solutions or decisions.

2.9.3 Modelling Techniques

Mathematical models of livestock systems fall into one of two generic categories: Simulation or optimisation (Bicknell, Edwards, Trafford, Tran, & Dooley, 2015). Simulation models imitate, step by step how a system behaves over time (Daellenbach & McNickle, 2005). For complex dynamic systems these models provide an ideal framework for calculating the performance of the system, especially when these systems involve random aspects. Simulation, however, does not allow for the calculation of the optimal solution. In contrast, optimisation models are mathematical models that seek to identify the optimal combination of activities. A common approach to optimisation is linear programming. This is explained in detail in the following section.

Models can also be deterministic or stochastic. A deterministic model is a model in which the uncontrollable inputs are assumed to be known and cannot vary (Anderson et al., 2013, p. 10). In contrast, a stochastic model is a model in which uncontrollable inputs are uncertain and subject to variation.

2.10 Linear Programming

Linear programming is a mathematical procedure, based on a system of linear equations, that involves maximising or minimising an objective function subject to constraints that limit the degree to which the object can be pursued (Anderson et al., 2013, p. 17; Hillier & Lieberman, 2005, p. 12)

For clarity of meaning, it should be noted that the word *programming* should not be confused with computer 'programs'. Rather, in the present context, the word *programming* is a synonym for planning and means "choosing a course of action" (Anderson et al., 2000, p. 35). In particular, programming refers to the planning of activities so as to achieve an optimal result (Hillier & Lieberman, 2005, p. 25). The adjective *linear* in Linear Programming refers to the fact that the ultimate plan is obtained by employing a mathematical procedure that involves linear relationships

(Lapin & Whisler, 2002, p. 262). The inherent assumptions within linear programming are further discussed later in this section.

The initial mathematical statement of the general problem of linear programming, along with its solution procedure, was first developed in 1947 by George Dantzig of the U.S. Department of the Air Force for use in military programming and planning problems (Dantzig, 1963). Being simple in its mathematical structure but powerful in its adaptability, linear programming has since become an important tool of modern theoretical and applied mathematics and is used to determine the efficient use or allocation of limited resources to meet desired objective (Gass, 2003, p. 1; Hazell & Norton, 1986, p. xii).

Although there is a variety of notations in common use (Gass, 2003, p. 68), the general linear programming problem follows the conventions from linear algebra and can be mathematically expressed as:

$$\max \text{or} \min Z = \sum_{j=1}^{n} C_j X_j$$

Such that

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i, \quad \text{all } i = 1 \text{ to } m$$

and

$$X_j \geq 0, \quad \text{all } j = 1 \text{ to } n$$

Where:

Z, is the objective function
X_j, is the level of the j^{th} activity. If n denotes the number of possible activities; then $j = 1$ to n
C_j = the coefficient of the objective function of the j^{th} activity
a_{ij} = the quantity of the i^{th} resource. Let m denote the number of resources; then $i = 1$ to m
b_i = The amount of the i^{th} resource available

There are four major aspects to a linear programming problem. The first requirement of linear programming problems is the specification of the objective function. This is a mathematical expression that is used to represent the criterion for evaluating solutions to a problem (Anderson et al., 2000, p. 18). In this expression, the coefficients linking activities to changes on the desired objective, the C_j coefficients, are termed the “cost coefficients” of the objective and hence the use of the literal coefficient C (Gass, 2003, p. 6).

The next requirement of linear programming problems is the specification of the alternative activities, their unit of measurement, their resource requirements, and any specific constraints on their production. In linear programming problems the factor x represents the different activities in the model. It is useful to note that activities within linear programming problems are not always explicitly expressed in the objective function (they are not multiplied by a C_j coefficient), but can be intermediate activities. Such activities are termed *tie* activities and link resource requirements of output activities. The resource requirements of tie and output activities are denoted by the a_{ij} coefficients which are called input-output or technological coefficients (Gass, 2003, p. 6).

The third requirement of linear programming problems is the specification of the fixed resource constraints. As explained by Anderson et al. (2000, p. 18), constraints are the "restrictions or limitations imposed on a problem". These constraints may be in the form of inequalities, less than or equal to $(\leq)$, greater than or equal to $(\geq)$ or equalities $(=)$. In the general mathematical description of linear programming given above, the constraints were presented as less than or equal to constraints. This is correct if the objective is maximisation. However, these general constraints should be presented as greater than or equal to constraints if the objective is minimisation (Paris, 2016).

A feasible solution to a linear programming problem is a decision alternative or solution that satisfies all constraints (Anderson et al., 2000, p. 19). In contrast, an infeasible solution is a decision alternative or solution that violates one or more constraints. Constraints may therefore be either binding or non-binding. A binding constraint implies that all of the resource is used up, or in other words, that the total amount of the resource consumed is equal to the amount available (Daellenbach, McNickle, & Dye, 2012, p. 369). A constraint that is not binding refers to the fact that some of the resource has not been used. In such a case the constraint is also referred to as having "slack" (Paris, 2016).

The final step of linear programming is to determine the activity levels such that the objective function is maximised or minimised subject to the specified constraints. This is done using the algebraic procedure known as the simplex method first developed by George Dantzig in 1947 (Anderson et al., 2000, p. 218; Dantzig, 1963; Hillier & Lieberman, 2005, p. 103). Although this procedure has since been revised and extended to improve its computational efficiency for modern computers, the principles of the solution procedure remain unchanged (Gass, 2003; Hazell & Norton, 1986, p. 21). A detailed explanation of the mathematics and the computational procedures of the simplex method have been extensively reviewed in such texts as Hadley (1962), Heady and Candler (1958), and Matousek and Gartner (2007), and is not presented here. Although linear programming problems can, in theory, be solved by hand calculations, this is only practical for small problems. Large models require the use of dedicated software that automatically performs the simplex routine or modifications thereof. Examples include Solver™ developed by Frontline Systems and Lindo™ developed by Lindo Systems Inc.

It is convenient for linear programming problems to be portrayed in a matrix[2] which shows all the coefficients of the algebraic statement of the model (Table 2.2). As explained by Hazell and Norton (1986, p. 11), this way of presenting a linear programming model is by convention called a tableau. When presented in this way, constraints are represented along the rows and the activities are represented in the columns. Another convention when representing linear programming problems in a tableau is that the fixed resource supply or the b_i coefficients are called the right-hand side, or RHS, of the problem (Ragsdale, 1995, p. 19). The left hand side, or LHS, of the constraint refers to the $f(x_1, x_2, \ldots, x_n)$ side. However, a confusing factor is that when developing large matrices, it is often easier to state the b_i coefficients on the left hand side of the problem. Also note that while the b_i coefficients have been stipulated as less than or equal ($\leq$) constraints in Table 2.2, constraints may also take the form of equality ($=$) constraints or greater than or equal ($\geq$) constraints.

Table 2.2 A linear programming tableau

Row name	**Columns**				**RHS**
	X_1	X_2	…	X_n	
Objective Function	c_1	c_2	…	c_n	Max (or Min)
Resource constraints:					
1	a_{11}	a_{12}	…	a_{1n}	$\leq b_1$
2	a_{21}	a_{22}	…	a_{2n}	$\leq b_2$
.	.	.	…	.	.
.	.	.	…	.	.
.	.	.	…	.	.
m	a_{m1}	a_{m2}	…	a_{mn}	$\leq b_m$

There are a number of assumptions implicit within a traditional linear programming model. These include optimization, fixedness, finiteness, certainty, non-negativity, continuity, homogeneity, additivity, and proportionality.

1. *Optimization:* In linear programming models it is assumed that an appropriate objective function is either maximised or minimized (Hazell & Norton, 1986, p. 13). The optimal solution is the term that describes the specific decision variable value or values that provide the "best" output for the model (Anderson et al., 2000, p. 19).

2. *Fixedness:* Linear programming models require at least one constraint to have a nonzero right hand coefficient. If this assumption does not hold, the value of the solution may be made

[2] A matrix is a rectangular array of mn numbers arranged in m rows and n columns.

infinitely large without violating any of the constraints. In such a case the model is said to be unbounded (Anderson et al., 2000, p. 63; Hazell & Norton, 1986, p. 29).

3. *Finiteness:* For a solution to be sought it is assumed that there are only a finite number of activities and constraints to be considered (Hazell & Norton, 1986, p. 13).

4. *Certainty:* All traditional linear programming models assume that all the a_{ij}, b_i, and c_i coefficients in the model are known constants (Hillier & Lieberman, 2005, p. 43). As such, linear programming models are categorised as being deterministic (Gass, 2003, p. 69). However, using a variety of different techniques, the traditional linear programming framework can be adapted to allow for the inclusion of uncertainty. Alternative approaches to risk programming are reviewed by Hardaker et al. (1991). Despite traditional linear programming being deterministic, it is notable that uncertainty of input data is often taken into account using techniques such as sensitivity analysis and post-optimality parametric programming (Hazell & Norton, 1986, p. 31).

5. *Non-negativity:* With respect to the possible values of variables, it is assumed that each variable must be non-negative (Gass, 2003, p. 13). Note that the non-negativity requirement of linear programming has not been included in Table 2.2, as by convention they are taken for granted in such linear programming tableaux.

6. *Continuity:* Also called the assumption of divisibility, the continuity assumption of traditional linear programming assumes that resources can be used and activities produced in quantities that are fractional units (Hazell & Norton, 1986, p. 13; Hillier & Lieberman, 2005, p. 42). In other words, all relationships are assumed linear and all the variables are assumed as being continuous. Where values are restricted to integer values the linear programming problem is said to be an integer linear programming problem. Although integer values allow for a more accurate representation of real-world problems, the difficulty with integer or mixed-integer linear programming approaches is that the additional requirement for integer values means that the problem is no longer linear and results in an exponential increase in computational requirement (Anderson et al., 2000, p. 16). Therefore, where possible, it is preferable to assume variables are continuous.

7. *Homogeneity:* Often taken as implicit, the specification of linear programming problems requires the assumption that all units of the same resource or activity are identical (Hazell & Norton, 1986, p. 13)

8. *Additivity:* In linear programming problems it is assumed that activities are additive in the sense that when two or more are used, their total product is the sum of their individual products

(Hazell & Norton, 1986, p. 13). In other words, it is assumed that there is no interaction effect between activities.

9. *Proportionality:* The proportionality requirement of linear programming is the assumption that "a change in the level of an activity x_j causes a proportional change in the resources used and in the corresponding term of the objective function" (Gass, 2003, p. 13). In other words, it is assumed that the objective function and resource requirements per unit of activity are constant regardless of the level of the activity used. Consequently, this assumption rules out any exponent other than 1 for any variable in any term of any function (whether the objective function or the function on the left-hand side of a functional constraint) in a linear programming model (Anderson et al., 2000, p. 35; Hillier & Lieberman, 2005, p. 38).

The assumptions of continuity, additivity and proportionality together define linearity in the activities, thereby giving rise to the name linear programming (Hazell & Norton, 1986, p. 13). The additivity and proportionality assumptions also mean that there are constant returns to scale and if all fixed resources are increased by a factor of proportionality k, then the value of the objective function Z also increases by k. In other words, if all resource supplies are doubled, then all the activity levels in the optimal solution will also double, as well as the optimal value of the objective function Z.

A final note on linear programming is that while the assumptions underlying linear programming are stringent, and must hold for all the rows and columns of a model, they do not have to hold for the production process themselves (Hazell & Norton, 1986, p. 14). Many ingenious methods of increasing the flexibility of the model are therefore possible without violating the assumptions.

2.11 Livestock Production Models

There are many different livestock production models (Bicknell et al., 2015; Bryant & Snow, 2008; Glen, 1987; Janssen & van Ittersum, 2007). Models have been developed using both simulation and optimisation techniques and range from simple enterprise-level models to complex whole-farm models that incorporate plant, animal, environmental and economic interrelationships (Pannell, 1996). In this section, an example of the different types of both simulation and optimisation livestock models are described. The focus is on pastoral livestock models and livestock models of systems as opposed to individual animals. Specific livestock system simulation models that are discussed include the Farmax, Grazplan, GrazMod, LincFarm, APSIM, WFM, FASSET,GPFARM and the IFSM models. Other simulation models that are also discussed include the models developed by Cruickshank, Thomson, and Muir (2009), Nugent and Jenkins (1993), and Shadbolt (1982). Specific livestock optimisation models that are discussed include the MIDAS, IDEA, and the GSL models as well as the models developed by McCall et al. (1999), Ludemann (2009), Woodford (1997), and Rendel, Mackay, Manderson, and O'Neill (2013).

2.11.1 Simulation Models

Farmax

In New Zealand, a common way to model livestock systems is using Farmax. Farmax is a whole-farm bio-economic decision support (planning) model and has been developed for dairy farms and for sheep and beef farms (Farmax, 2015). Farmax Pro is the sheep and beef version of the model and was developed by AgResearch using the original Stockpol model (Marshall, McCall, & Johns, 1991). Farmax Dairy Pro is the dairy version of the model and is a combination of the pasture module of Farmax Pro and the animal components of MOOSIM (Bryant et al., 2008). Both Farmax models are Windows applications developed using Delphi® and use monthly estimates of pasture growth, and farm and flock/herd information to predict animal, farm and financial performance for different management scenarios (Bryant et al., 2010). Farmax can be used in long term or short term modes (Bingham, 2009). The short term mode is used to plan for the current season while the long-term mode is designed to describe the farm's average year and is designed for longer term strategic decisions.

The first step in using Farmax requires defining the farm resources. Land area, starting pasture cover and pasture quality is defined for each pastoral land unit on the farm. Potential pasture growth rates for each month are then chosen. Nitrogen applications, the area of land in crops, and the period out of the grazing area are specified. Pasture conservation and feeding activities are also defined.

A key component of Farmax models is the integration of a pasture sub model which captures the biology of pasture growth. The pasture module is described by Bryant et al. (2010) and Marshall et al. (1991). This pasture module adjusts the specified (or potential) monthly growth rate after calculating lost potential and decay. Lost potential occurs progressively as pasture cover falls below or increases above critical limits and represents either the lag in pasture re-growth when there is a low leaf area, or the slowing of growth as pastures near ceiling leaf area. In the model, pasture decay is calculated through a method of partitioning the total pasture mass into pools of green, stem and dead material (Bryant et al., 2010). As pasture cover increases, the proportion of stem and dead material increases. In this way, pasture quality declines as pasture covers increase.

After defining the land resources of the farm, animal production enterprises (e.g. sheep or beef) and animal groups are defined. Animals are defined based on their age, breed, initial liveweight and body condition score, whether they are pregnant or lactating, percentage mature weight and genetic merit. The model generates an expected distribution of body condition scores and liveweight for the flock/herd. Dates for animal activities such as mating, shearing, and the timing of stock sales and deaths are inputted. Progeny of breeding females can be kept or sold and animals can be grazed on or off the property at any stage. After the animal system has been defined, the energy based animal module within Farmax calculates maintenance requirements, lactation, body energy reserves, growth requirements and pregnancy requirements. “Feed intake is then estimated based on the animals’ requirements for maintenance, growth and pregnancy (if relevant)” (Bryant et al., 2010).

After pasture growth rates have been entered and feed intakes have been predicted for the specified animal production activities, pasture cover and quality is predicted. The Farmax model then calculates if the system is feasible. The livestock production system is considered infeasible if pasture cover is below the minimum cover to meet the desired level of animal performance.

The outputs of the Farmax model include summaries of land use, net pasture growth, feed supply and demand. Outputs of the model also include reconciliation of pasture and stock, and production and financial data. For example, the model can be used to calculate the amount of meat produced and can predict farm profitability.

Through successive years of research and development, Farmax has been refined to sufficiently simulate the production output expected for a specified production system. A strength of the model is that it is able to capture systems interrelationships and incorporate the feedback effects inherent within livestock production systems. However, for the purpose of strategic farm planning across a range of feed supply environments, a problem is that Farmax is a supply-driven model and is built in relation to a specified feed supply curve. The issue, then, is that the recommendations from a Farmax model will not apply to farms with a different feed supply situation. This is particularly important for New Zealand pastoral farms as feed supply varies from farm to farm and region to region (Valentine & Kemp, 2007, p. 3). In other words, the model generally only works within defined parameters within an existing system and cannot be used to simulate large departures from current systems (Bicknell et al., 2015). Being a simulation model, Farmax will also not identify optimal systems and resource requirements.

Grazplan

The GrazPlan suite of models first originated in 1985 and were developed for the Australian livestock grazing industry (Bryant et al., 2010).The GrazPlan suite of models include the GrassGro, GrazFeed and AuzFarm Models (www.grazplan.csiro.au). The assumptions used in the GrazPlan simulation models are described in detail by Donnelly et al. (1997), Freer et al. (1997), and Moore et al. (1997). Further adaptations and evolution of the original models are described by Donnelly et al. (2002).

GrazFeed, the first of the GrazPlan models was developed in conjunction with the Standing Committee on Agriculture (SCA, 1990) publication "Feeding Standards for Ruminants" and allows for the calculation of daily nutritional needs of any breed or class of sheep and cattle. This model outlines the energy and protein requirements of sheep and cattle and takes into account the effects of selection and substitution by grazing stock. GrazFeed can be applied to any temperate or tropical grazing system and can also accommodate management systems which restrict pasture intake, such as strip grazing, cut-and-carry systems and feedlotting. The model predicts conception rates, lambing percentages and mortality rates of sheep, lambs and cattle based on animal size, body condition of the animal and weight loss during late gestation and around parturition.

The GrassGro model builds on the nutritional calculations used in GrazFeed and simulates a whole grazing enterprise in which pasture growth is linked to the higher-order plant and animal models with local weather records, soil properties, management and financial details. The supply and quantity of pasture is simulated on the basis of soil and pasture type, with pasture growth driven by historical daily weather data. In the model, multiple paddocks can be specified with different soil and pasture parameters possible for each. Probability and cumulative probability distributions functions for variables such as average fleece weight, the amount of supplements required, and available pasture biomass are estimated.

The AusFarm model has the capability of both GrazFeed and GrassGro but goes several steps further in the description of complex biological systems. Its structure allows models of farm components to be configured and co-ordinated with an infinitely flexible set of management rules. AusFarm is primarily used by experts for large projects and research.

GrazPlan has been extensively parameterised and simulations validated for pasture and animal data throughout Australia (Cayley, Hannah, Kearney, & Clark, 1998; Clark, Austen, Prance, & Ball, 2003; Clark, Donnelly, & Moore, 2000; Robertson & Friend, 2013) and has been used for many applications. For example, over a 53 year simulation period, Alcock, Harrison, Rawnsley, and Eckard (2015) used the GrassGro simulation model to investigate the impact of animal genetic parameters and flock management on greenhouse gas emissions and the wool productivity and whole-farm profitability on sheep farms in southern Australia. Other applications of the model include Harrison et al. (2014), Donnelly, Freer, and Moore (1998), Alcock and Hegarty (2011). While each GrazPlan model can stand alone, they can also be integrated with APSIM using the Common Modelling Protocol (Moore, Holzworth, Herrmann, Huth, & Robertson, 2007).

Overall, the GrazPlan suite of models is similar to the Farmax simulation model and is defined as a supply-driven model with animal performance and livestock systems determined in reference to specified feed supply and environmental conditions.

GrazMod

GrazMod has been developed for Australian and New Zealand grazing systems and refers to three models with the same underlying biophysical simulation model (Johnson et al., 2008). These models are the SGS Pasture Model, EcoMod, and DairyMod. The SGS Pasture Model was developed as part of the Sustainable Grazing Systems (SGS) Project (Johnson, Lodge, & White, 2003). The same underlying biophysical model was used and the interface revised for the dairy industry (DairyMod). For the third model (EcoMod), the interface was then further revised to allow for greater management options. The GrazMod suite of models include modules for pasture growth and utilisation by grazing animals, water and nutrient dynamics, animal physiology and production, and a range of options for nutrient return, pasture management, irrigation and fertiliser application (Eckard, Cullen, & Snow, 2008).

The pasture growth module includes calculations of light interception and photosynthesis and includes calculations of growth and maintenance respiration, nutrient uptake and nitrogen fixation, partitioning of new growth into the various plant parts, development, tissue turnover and senescence, and the influence of atmospheric CO2 on growth. The treatment of CO2 also includes the plant nitrogen response, which affects pasture quality, and stomatal conductance which affects water use.

The model allows up to five pasture species in any simulation, which can be annual or perennial, C3 or C4, as well as legumes. The water module includes rainfall and irrigation inputs that can be intercepted by the canopy, surface litter or soil. The nutrient module incorporates the dynamics of inorganic nutrients (including leaching) and soil organic matter.

The animal module has a sound treatment of animal intake and metabolism including growth, maintenance, pregnancy and lactation. There are options to select sheep (wethers or ewes with lambs), cattle (steers or beef cows with calves), dairy cows, and deer. The farm management module describes the movement of stock around the paddocks as well as the strategies for conserving forage, and incorporates a wide range of rotational grazing management strategies that are used in Australia and New Zealand (Johnson et al., 2008).

Up to 100 independent paddocks can be defined to represent spatial variation within a notional farm. Paddocks can have different soil types, nutrient status, pasture species, fertiliser and irrigation management, but are subject to the same weather. Supplement conservation rules can be specified. Management options include commonly used rotational grazing management strategies and continuous grazing with fixed or variable stock numbers. A cutting regime simulates calculation of seasonal pasture growth rates.

Currently, simulations can run for 150 years which could be extended if necessary. A number of developments to the initial GrazMod model are described by Eckard et al. (2008). These include developments to the CO2 responses, animal routines, and the inclusion of atmospheric nutrient inputs.

The SGS model has been shown to adequately predict pasture production at a range of sites in Australia and New Zealand (Cullen et al., 2008; Lodge & Johnson, 2008) and has been applied to a range of research questions including questions on climate variability, drought, and the impacts of climate change (Bryant, Hoogendoorn, & Snow, 2007; Chapman, Kenny, Deca, & Johnson, 2008; Cullen, Eckard, Johnson, Bryant, & Rawnsley, 2007; Eckard et al., 2008; White, Johnson, & Snow, 2008).

LincFarm

Another simulation model is the Lincoln University sheep farm simulation model, LincFarm (Cacho et al., 1995; Finlayson et al., 1995). This is a whole-farm simulation model that simulates New Zealand pastoral sheep production systems and predicts animal conception rates incorporating the effect of liveweight change prior to mating (Cacho et al., 1995). It also simulates lactation, maintenance, growth (including genetic variation in protein deposition), pregnancy and wool production (Finlayson et al., 1995). The model also explicitly takes animal-pasture interactions into account and if the mob goes below a critical weight limit due to feed shortage, the model will assume a proportion of animals die due to starvation/malnutrition. Although the pasture growth module incorporated within the LincFarm model is simple, it allows for the representation of site-specific factors such as soil and weather which influence daily and seasonal variations in pasture growth (Cacho et al., 1995). Since its originally development in the 1990s, the model has subsequently been modified to account for risk (Gicheha, 2011; Gicheha, Edwards, Bell, Burtt, & Bywater, 2012).

The model simulates animal production and farm management well. However this model is also developed using a feed supply driven approach.

APSIM

The Agricultural Production System Simulator (APSIM) model is a framework of biophysical modules that simulate biological and physical processes in farming systems. However, this model has a particular emphasis on cropping systems. Applications including modelling soil water, nitrogen balance and nitrogen leaching; growth of a wide range of arable crops, interactions between crops, dryland and irrigated salinity mitigation and/or adaptation; climate change scenarios; production risk; different row configurations of seed planting; gene-gene interactions; and gene-environment interactions (Bryant & Snow, 2008). Although not directly relevant to livestock production, the APSIM model has a flexible architecture which has allowed other livestock models such as the GrazPlan suite to be linked into the APSIM framework (Moore et al., 2007). The original APSIM model is described in detail by Keating et al. (2003) with subsequent developments described by Holzworth et al. (2014).

Although widely used, both as a research tool and by farmers (Hunt et al. 2006), the APSIM model is less relevant for the purpose of this study. The strength of the APSIM model is for its use as a pastoral agro-ecosystem model rather than detailed modelling of livestock feed demands and animal production.

WFM

Specifically related to dairy livestock systems, Dexcel (now DairyNZ) in New Zealand developed a bio-economic Whole Farm Model (WFM) that links published sub models for cow metabolism together with climate-driven pasture models (McCall & Bishop-Hurley, 2003). The different components of the model include weather, soil, pastures, paddocks, animals, decision rules and reporting (Beukes et al., 2008; Thorrold, 2005). Inputs include the area of paddocks, minimum grazing residual and pasture composition, as well as the amount of supplements on hand (Wastney et al., 2002). Pasture growth is driven by weather and soil moisture assumptions and influenced by soil fertility, current pasture cover and recent grazing history (Thorrold, 2005). In the model, each animal is represented using the "Molly" sub model developed by Baldwin, France, Beever, Gill, and Thornley (1987), with model inputs being age, breed, genetic merit, liveweight, calving, mating and drying-off dates. Key model outputs include milk production, pasture growth, animal liveweight, and economic farm surplus and return on assets. Validations and applications using the WFM model include Wastney et al. (2002) who showed that the WFM model was able to predict pasture growth, milk yield and cow live weight for a spring calving herd under New Zealand conditions. The model was also used by Jensen, Beukes, Clark, and Macdonald (2005) to determine the effect of stocking rate on feed conversion efficiency (g milk solids/kg DM intake) which was then compared against the results obtained in the Resource Efficient Dairying farmlet trials (Macdonald et al., 2001).

FASSET

The Farm ASSEssment Tool (FASSET), developed in Denmark is a whole-farm dynamic model that simulates production, economics and pollution of livestock production systems (www.fasset.dk). FASSET is a deterministic model and uses a daily time step for most simulations. Version 1 of the model described only pig and arable farms but utilised an economic optimisation model that simulated crop rotations and fertiliser/manure use (Berntsen, Petersen, Jacobsen, Olesen, & Hutchings, 2003; Berntsen, Petersen, Olesen, Eriksen, & Soegaard, 2005). This construction proved difficult to implement and maintain so has been omitted from Version 2 in favour of the progressive inclusion of decision-making within FASSET itself. FASSET v 2 has also been extended to describe dairy and beef cattle.

More suited to housed livestock systems, the FASSET model has limited relevance for the purposes of this research. The strength of the model is in its simulation of soil nutrient dynamics, crop or pasture production and spatial variations in soil properties (Bryant & Snow, 2008).

GPFARM/iFARM

GPFARM is a simulation model developed in the United states from 1994 (Ascough et al., 1999). Its aim was to model the long term effects of alternative Great Plans ranching practices on environmental and economic sustainability. The model has now been upgraded to iFarm (Integrated Farm and Ranch Management) which incorporates extended crop and forage modules. The animal production model simulates cow-calf operations on native grasslands and has been used to investigate the impact of alternative management strategies such as changing stocking rate, adopting rotation grazing and alternative birth, weaning and sale dates. Overall, the GPFARM and iFarm models are considered not very relevant for the purpose of assessing biological efficiency of pastoral livestock systems. The strength of GPFARM is to predict forage production of different plant functional groups. It has detailed sub models relating to feed supply. For example, modules describe crop growth, evapotranspiration, water balance, soil erosion, and weed dynamics. However, the cattle module can be used to explore different management scenarios such as changing the stocking rate, adopting rotational grazing, and different birth, weaning, and sale dates (Ándales et al., 2005).

IFSM

The Integrated Farm System Model (IFSM) is a simulation model of dairy and beef production. The model has nine major sub models including crop and soil, grazing, machinery, tillage and planting, crop harvest, crop storage, herd and feeding, manure handling, and economic analysis (Rotz & Coiner, 2006). IFSM was formally known as DAFOSYM and was originally a diary-forage model (Rotz, Black, Mertens, & Buckmaster, 1989; Savoie, Parsch, Rotz, Brook, & Black, 1985). The model is based on US pasture-based dairy and crop systems but is adaptable to temperate regions (Bicknell et al., 2015). The IFSM model incorporates a high level of detail for biophysical components but focusses heavily on pasture (skinner, Corson, & Rotz, 2009). The IFSM model also allows for comprehensive representation of machinery. Due to the detail of input assumptions and their specific nature, this model has limited use as a tool for strategic livestock system analysis.

Other Simulation Models

Another simulation model is the sheep production model described by Cruickshank et al. (2008). This model was written in Microsoft Excel™ and is constructed to simulate a self-contained sheep production system. It allows for variation and simulation of the effects of numerous farm production traits including sire, ewe and lamb parameters as well as flock structure. Data used in the construction of the model has been obtained from the Poukawa Elite Lamb flock which involves some 6,000 ewe records from four genotypes and 8,100 lamb records over 8 years (Cruickshank et al., 2009). This model was used to determine the effect of changing ewe liveweight, lamb growth rate, ewe mortality, ewe culling, reproductive performance and hogget lambing on production efficiency and methane output of the sheep flock. In comparison to other models, this model can be considered an enterprise system level model and does not incorporate plant-animal interactions at the farm level. For a specified number of ewes (1000 ewes plus replacements) and specified parameters such as ewe liveweight and lamb growth rate, the model calculates total feed demand of the system as well as total meat carcass and methane output. The focus of the model is on describing how animal production parameters impact on total system feed demand and production (and methane output) and does not consider how animal feed demands are to be satisfied. As the model is not specific to a particular farm, model findings are generic. However, modelling is set up in respect to a fixed number of animals with total annual feed demand an output of the model. In practice, due to the inherent difficulty in altering total feed supply on pastoral farms, stocking rate would normally be a function of the desired livestock system and performance parameters. A further weakness of the model is that it is an annual model and does not calculate the seasonal profile of feed demand.

Nugent and Jenkins (1993) used a deterministic computer simulation model to estimate the effects of age of culling on biological efficiency defined as grams of empty body weight equivalent value of market lamb, cull ewe, and wool output (EBW) per kilogram input of total digestible nutrients (TDN). It was found that depending on precocity, EBW/TDN was highest when ewes were culled at four or five years of age.

Shadbolt (1982) constructed a simulation model incorporating biological, physical and economical components of a lamb production system on an irrigated farm. This model was then used to test the effect of alternative lamb drafting strategies.

Sise, Shackell, Byrne, Glennie, and Amer (2009) describe a stochastic simulation model which was used to simulate genetic effects, inherited from the ewe's sires, in breeding ewes and their lambs for key performance recorded traits. The traits simulated include weaning weight, mature weight, number of lambs born, lamb survival, and longevity. This model is an economic model and does not model the energy cost and therefore the biological efficiency of the livestock production system. This model is also based on a component level of analysis and uses a component measure of efficiency rather than a systems measure of efficiency.

The New Zealand Forest and Agriculture Regional Model (NZ-FARM) was developed by Landcare Research to help decision makers assess the potential economic and environmental impacts of policy on regional land use. As this model is a regional model, and developed primarily for policy analysis, it does not incorporate the “rich farm-level detail required for a farm systems modelling project” (Bicknell et al., 2015) and is not relevant for the purposes of this research.

Taylor, Moore, Thiessen, and Bailey (1985) use an empirically based simulation model to examine the overall efficiency of conversion of feed energy to lean meat in traditional, twinning and sex-controlled beef production systems. Other simulation models of cattle (dairy) systems include the Udder, e-Dairy, Dairy Wise, and SIMSDairy models and are reviewed by Bicknell et al. (2015). Other early simulation models are reviewed by Glen (1987).

2.11.2 Optimisation Models

MIDAS

In Western Australia, a whole-farm linear programming model, MIDAS (Model of an Integrated Dryland Agricultural System), has been developed to investigate how limited resources should be allocated to alternative enterprises (Morrison, 1986). A detailed description of the MIDAS model is given by Kingwell (1986). The MIDAS model has a joint emphasis on biology and economics. There are several versions for representative farms in different regions of Western Australia, but all include components for crops (cereal and legume), pastures, sheep, feed (crop residues, grains, pastures), machinery and finance. They are detailed in their representation of soil types and potential enterprise rotations, with different production figures for each phase of each rotation on each soil type (Pannell, 1996). The objective function represents profit maximisation. Although the original MIDAS model was deterministic, it has been adapted to account for risk. An example of an application of the MIDAS model is given by Young, Thompson, Curnow, and Oldham (2011) who investigate the impact of different liveweight profiles of Merino ewes on whole-farm profit.

In comparison to simulation models such as Farmax, MIDAS allows for the calculation of optimal systems. However, like Farmax, the MIDAS model is a supply-driven model with animal production an output calculated in respect to a specific environmental context.

IDEA

The integrated dairy enterprise analysis (IDEA) model is a deterministic, steady-state optimisation model of pastoral dairy farming systems (Doole, Romera, & Adler, 2013). Unlike many other optimisation models, the IDEA model uses non-linear rather than linear programming techniques. The optimisation algorithm used is the CONOPT solver in the General Algebraic Modelling System (GAMS). The objective function involves the maximisation of operating profit or minimisation of GHG emissions (Doole, 2014).

Also, another unique feature of the IDEA optimisation model is that pasture intake is limited by herbage allowance and pasture growth and digestibility depends on defoliation intensity and the duration between grazing events (Doole and Romera 2013). The IDEA model therefore provides a detailed description of many of the key biophysical processes observed within grazing systems that are absent from other whole-farm models that utilise optimisation (Ludemann, 2009; McCall et al., 1999; Stott, Milne, Goddard, & Waterhouse, 2005).

A detailed description of the equations used in the model are presented in Doole et al. (2012). A central concept of the IDEA model is the balancing of energy supply and demand. The supply of energy is obtained from grazed pasture and supplements, while energy demand depends on individual cow attributes and herd structure. There are nine sub modules. The sub modules that define feed supply are the land use module (which specifies the area grazed, conserved and cropped), the pasture module (which specifies the herbage mass available and the ME concentration of grass), the pasture utilisation module (defined by stocking intensity), the supplement module (which defines the amount of supplements used and the ME concentration of supplements), the substitution rate module, and the pad module (which specifies the time on pasture). The cow module determines feed demand and specifies the ME demand per cow type, the cow intake capacity, milk production per cow type, and the number of cows per type. The two remaining modules are the integration module (which ensures that the ME intake is greater to or equal to the ME demand and ensures that the potential intake is greater or equal to the DM intake) and the profit module (that sets revenues, operating costs and fixed costs).

Supplementary feeds that are available within the IDEA model include grass silage, maize silage, palm kernel expeller (PKE), and turnip crops. A large number of cow types (17,640) are defined in IDEA to allow a rich description of herd structure (Doole et al., 2012). Cow attributes that impact on feed demand include growth, conception, pregnancy, body condition, liveweight, intake, lactation length, and milk production. Herd structure decision variables include cull policy, age distribution, calving date and intake control.

An example of an application of the IDEA model, is given by Romera and Doole (2015) who use the model to investigate the interrelationship between intake per cow and intake per ha. Also, Adler, Doole, Romera, and Beukes (2013) show how the IDEA model can be adapted to investigate the impact of grazing systems on GHG emissions.

Albeit dairy, the IDEA model is a comprehensive farm-level model and is very relevant for the investigation of biological efficiency within livestock systems and is able to capture key biophysical processes within the grazing system. However, the model is also a supply-driven model and focuses on modelling livestock productivity in relation to a specified feed supply situation. For example, the model incorporates animal-plant-supplement dynamics and moderates production outcomes as a result of the impact of grazing mass, pasture growth, digestibility, rotation length, intake regulation, pasture utilisation and stocking rates on feed supply. This model is therefore suited to the investigation of biological efficiency in relation to a particular farm scenario but is less suited to the strategic investigation of generalised drivers of livestock productivity across a range of contexts.

GSL

The Grazing Systems Ltd (GSL) linear programming model reported by Anderson and Ridler (2010) and reviewed by Hurley, Trafford, Dooley, and Anderson (2013) is a bio-economic model of a dairy grazing system. The GSL model is constructed by Jade software (Hurley et al., 2013) and is deterministic (the model assumes that coefficients, costs and constraints are known with certainty). It optimises animal production against energy supply from pasture, crops and supplements. The model also allows for nitrogen applications and grazing off farm. Pasture supply constraints are specified as pasture covers through time. The objective function maximises cash surplus. Applications of the GSL model include an investigation of the optimum herd replacement rate (Ridler, Anderson, & McCallum, 2014) and an investigation on the optimal dairy system in a sensitive catchment (Sulzberger, Phillips, Shadbolt, Ridler, & McCallum, 2015).

Hurley et al. (2013) conclude that the GSL model does provide another useful addition to the “tool box” of farm system decision support and simulation programmes. However, like other models already discussed, the GSL linear programming model is a supply-driven model with the model outputs (and the associated recommendations on optimal livestock systems) being specific to the feed supply assumptions used. For example, “the user defines inputs which then apply to a unique situation that the linear programming model is analysing” (Anderson & Ridler, 2010).

Other Optimisation Models

McCall et al. (1999) present a comprehensive linear programming model used to compare optimal dairy systems in New Zealand and the Northeast United States. This model was developed to determine optimum pasture management strategy (rotation lengths), feed input, stocking rate, calving date, lactation length, and associated milk production in order to maximise gross margin. Similar to IDEA, the model comprises a feed supply and a feed requirement component, with feed management activities linking supply and consumption. Components of feed supply were grazed pasture, nitrogen fertilised pasture, pasture conserved as silage, concentrates (grain), and corn and alfalfa silages. Cow production variables included calving date, length of lactation, and stocking rate. In the model, the grazing strategy was optimised by varying the rotation length.

Ludemann (2009) developed a deterministic linear programming model of a sheep livestock system. This bio-economic model was modelled at the whole-farm level and was used to determine the effect of increasing ewe prolificacy (lambs born per ewe lambing) on total farm profitability. As this model was constructed for a specific purpose (to investigate ewe prolificacy), model adaptations are required if this model is to be used to investigate the impact of a wider range of production parameters. The model is also supply-driven and therefore conclusions on optimal livestock systems are specific to the pastoral environment modelled.

An example of a linear programming model for deer is given by Woodford (1997). This model is also a bio-economic deterministic steady-state model. However, in contrast with Ludemann (2009), the model is demand-driven. In this approach, animal numbers and seasonal feed demands are determined endogenously within the model based on the relative proportions of each animal class and on the energy requirements per animal to reach specified performance levels (Woodford, 1997, p. 162). Therefore, while overall system feed demand is an input, seasonal feed demand is calculated as an output and is a function of performance parameters and animal numbers.

Rendel et al. (2013) describe a linear programming sheep, beef and deer farm model developed at AgResearch. This model is a deterministic steady-state farm resource allocation model and optimises the use of farm resources (land which is used for pasture and crop production; and sheep, cattle, including dairy grazers, and deer) whilst maximising profit (EBITDA). The model is a new generation whole-farm planning model in that, in departure from the use of total farm and average data for decision making, the model allows for the land area to be split into any number of land management units (LMUs) with optimal livestock systems computed in reference to these individual LMUs. The model therefore accounts for real-world complexity and takes into account areas of the farm that have differing characteristics (such as pasture growth rate, slope, and soil characteristics). The model incorporates a feed budget, stock reconciliation and financial budget. The user supplies pasture growth rates, minimum and maximum acceptable pasture covers for each LMU, animal performance, farm costs and market prices (Rendel et al., 2013). Additional constraints can be placed on individual LMUs. The optimisation routine uses this information to identify the mix of production enterprises and management regimes that maximises profit while balancing feed budget and reconciling livestock numbers. Animal inputs for each species include liveweights, growth rates, reproductive rates (scanning and weaning percentages), mortality rates, parturition date, weaning date, cull dates and replacement rate. Sheep and cattle requirements are estimated using GrazPlan equations (Freer, Moore, & Donnelly, 2012) and the deer feed requirements using Dryden (2011) and NRC (2007). The model's strength is that it can be used to explore the contribution of each LMU to business performance. This approach has benefit in that model outputs will more accurately reflect a real farm which may have many different LMUs. However, with accuracy for a given situation comes a lack of generalisable information useful for strategic decision making across a range of contexts.

An early linear programming model of a sheep production system is described by McGregor (1979) which was used to determine the optimal stock policy for fat lamb producing farms under dryland and irrigated conditions. The focus of the model was to determine the optimal age ewes should be culled. It was found that ewes should be culled at five and six years of age under irrigated and dry-land conditions respectively. This model was constructed for a specific purpose (to investigate ewe longevity), with the model framework not set up to allow for systems interactions that result from changes to other production parameters. The model is also characterised as a supply-driven model with feed supply constraints set in reference to dryland and irrigated Canterbury farms.

A further optimisation model is the model developed by Herd, Bootle, and Parfett (1993) which was used to examine the overall efficiency of converting feed energy to lean meat in traditional, twinning and sex-controlled beef production system.

Olney and Kirk (1989) present a small linear programming model of a Western Australian dairy farm. Berentsen and Giesen (1994) describe another linear programming model of a dairy farm with this model set up in reference to a dairy system in the Netherlands. In this model, pasture growth is defined is defined on an annual basis and its quality is fixed. However, Berentsen, Giesen, and Renkema (2000) extended the model to incorporate the implications of seasonal pasture growth and spatial diversity in management.

Other optimisation models of dairy systems include the linear programming model described by Stott (2008) and Stott et al. (2005) as well as the INTSCOPT and CamDairy models (Bicknell et al., 2015). The Integrated Suckler Cow Optimisation model (INTSCOPT) is a bio-economic whole-farm optimisation model developed for pasture-based dairy farms in lowland Switzerland that includes livestock, fodder and nutrient. In contrast, the CamDairy model was first developed in Australia in 1984 and is primarily a dairy nutrition model and is particularly detailed at the individual cow level (Bicknell et al., 2015).

2.12 Summary and Conclusions

Efficiency is a measure of how well resources are used in a given activity (Daellenbach & McNickle, 2005, p. 13). Biological efficiency is defined as the efficiency of biological processes (Spedding et al., 1981, p. 4) and can be expressed in many different ways depending of the point of view and level of analysis. However, for meat production from livestock, and within the context of pastoral production, biological efficiency can be measured as the efficiency of conversion of feed energy to meat carcass (hence the term "feed conversion efficiency") and can be expressed as the total annual kg of meat carcass produced per MJME that is eaten by the livestock system per year.

Being a biological system, livestock systems are characterised by a complex set of interrelated activities and interactions. As such, "the whole is greater than the sum of its parts" (Daellenbach & McNickle, 2005, p. 39) and analysis of livestock systems therefore requires a systems-thinking approach. Another fundamental attribute of pastoral livestock production is feed supply variability throughout the season. For feasible livestock systems, this requires feed demand requirements to match with feed supply. Therefore, production strategies aimed at increasing feed conversion efficiency must also consider the seasonality of feed demand required by the livestock system.

Models, by definition, are simplifications of reality and are able to help explain interrelationships and interactions within complex systems. However, while many simulation and optimisation models of livestock systems have been developed, each model relates to a defined purpose (Spedding, 1976). Although existing simulation models such as Farmax, LincFarm, and GrazPlan are able to confidently simulate the feasibility, biological efficiency and profitability of farming systems, these models are based on specific feed supply assumptions. This is also true for existing whole-farm optimisation models such as MIDAS, IDEA, GSL and the sheep optimisation model developed by Ludemann (2009). Given the seasonality in pasture growth and the variability in the pattern of feed supply throughout New Zealand (Figure 2.1), many of these existing models therefore have limited ability to be used for strategic farm planning across a range of environmental conditions. The recommendations from many existing models are specific to the particular scenario in which they were developed.

Consequently, from a decision-making and strategic planning perspective within the context of pastoral agriculture, there is a need to develop a generic approach to assess the feed conversion efficiency of livestock production systems. Accordingly, in contrast to the supply-driven approach that has traditionally been used, an alternative approach is to reverse the traditional modelling method and start with animal feed demand.

Such an alternative approach has value where the focus, rather than being on feed supply, is on the requirement necessary to meet specific animal performance levels and the implications thereof for:

a.) Biological efficiency;
b.) Seasonality of feed demand; and
c.) Systems economics related to alternative feed supply functions and their associated costs.

This demand-driven approach is a change in paradigm in livestock modelling and has strength in that conclusions derived from model findings are generic and not limited to a specific feed supply context.

The focus of this research is the sheep livestock production system. In Chapter 3, key parameters of this system are described and the possible effect of these parameters on both feed conversion efficiency and whole-of-system feed demand are discussed. Therefore, while this chapter took a general approach to get to the knowledge gap, the following chapter concludes with the specific knowledge gap as applicable to the sheep livestock system.

Chapter 3
The Sheep Livestock System

3.1 Introduction

The Red Meat Sector Strategy Report, commissioned by Beef and Lamb New Zealand and the Meat Industry Association of New Zealand, identified improved farm output per hectare as a major opportunity for improved profitability within the red meat sector (Deloitte 2011). This increase in output can come from increased feed production, or from more efficient use of feed by more productive animals, or from a combination thereof. While feed production (or factors affecting feed supply) are therefore important, this research focuses on the animal production side of the equation.

In mathematics, a parameter is a coefficient that links input and output variables (Forsythe & Walker, 1976). Assuming the purpose of the sheep meat livestock production system is to convert feed energy into meat carcass output, the aim of this chapter is to discuss how key livestock parameters may impact on whole-of-system feed conversion efficiency. Also, given the pastoral nature of New Zealand sheep farming and the associated seasonality of feed supply, livestock strategies that improve feed conversion efficiency must be evaluated in terms of feed demand seasonality. This chapter therefore also discusses how the key parameters of the sheep livestock system impact on the seasonality of feed demand.

While there are numerous parameters influencing the output of sheep meat relative to feed input, key parameters include lambing percentage, lamb growth rate, ewe size, target carcass weight, hogget lambing, and the age of ewe culling. Key parameters of the sheep livestock system also include mortality rate, ewe numbers and mating date. A number of parameters not investigated include ram size, weaning age, lambing spread, and the purchase of store lambs from off-farm. The choice of parameters investigated in this chapter was judgmental, and this choice was made in discussions between the author and the supervisors of this thesis.

At the conclusion of this chapter, the gap in knowledge is presented.

3.2 Lambing Percentage

Due to their ability to have multiple ovulations, sheep can give birth to multiple lambs (Hanrahan, 1980). Lambing percentage is commonly used to describe the reproductive performance of ewes and can be defined as the percentage of lambs tailed per ewe mated (Geenty, 1997). Average litter size is another measure of reproductive performance and is defined as the number of lambs born per ewe lambing.

For sheep, reproductive performance varies widely with individual litter sizes of up to seven lambs born per ewe being reported (Davis, 2004). However, even in high fecund breeds, the proportion of ewes with litter sizes greater than three lambs born per ewe is low (Amer, McEwan, Dodds, & Davis, 1999; Davis, Kelly, Hanrahan, & Rohloff, 1983; Hinch, Crosbie, Kelly, Owens, & Davis, 1985; Muir & Thomson, 2009). For example, from 64 flocks in the South Island, Kelly (1982) found that the mean number of lambs born per ewe lambing ranged from 1.0 to 1.9 in each flock. Important factors that influence reproductive performance include genetics, nutrition and management practices such as vaccinations against disease and are discussed in detail in *A guide to improved lambing percentage* (Geenty, 1997).

Reproductive ability impacts on both feed conversion efficiency and the seasonality of feed demand as a result of the effect of ewe maintenance energy requirement per lamb, pregnancy and lactation energy requirements, birth weight, lamb survival, lamb growth rate, and as a result of changes in ewe liveweight.

<u>The effect of lambing percentage on the ewe maintenance energy requirement per lamb:</u>

Maintenance energy costs are defined by Nicol and Brookes (2007) as the amount of energy needed for the basic processes of the animal to sustain life. For breeding ewes this can make up as much as 60% of the total amount of feed eaten in a year (Nicol & Brookes, 2007). This feed is required irrespective of the level of production that is achieved by that ewe and can therefore be considered a fixed cost or feed overhead. As the number of lambs born per ewe increases, the maternal overhead feed costs per unit of production will reduce, thus increasing feed conversion efficiency.

<u>The effect of lambing percentage on total pregnancy and lactation energy requirements:</u>

In sheep nutrition, pregnancy requirement refers to the amount of energy required by the ewe to support pregnancy (Nicol & Brookes, 2007). Primarily, this is a function of litter size. As litter size increases, although the energy costs per lamb born will decrease as a result of lower birth weights, total ME requirements for pregnancy increase significantly. For example, assuming that the total energy requirements of pregnancy are 50 MJME per kg lamb birth weight (Nicol & Brookes, 2007, p. 155), the total pregnancy energy costs for a single lamb of 5.5 kg is 275 MJME. In comparison, triplet lambs of 3.5 kg each will require a total of 525 MJME for pregnancy. This is nearly double the pregnancy requirement of a single lamb.

Lactation energy requirement is the sum of the energy required for milk production and the additional energy obtained from pasture by the lamb during the lactation period (Nicol & Brookes, 2007). The number of lambs born per ewe influences the energy required for milk production because ewes with multiple lambs produce more milk than similarly-fed ewes with singles (Litherland, Bryant, & Chicota, 2007, p. 11; Peart, Edwards, & Donaldson, 1975). For example, Geenty (1979) found that peak milk production was 2.3 litres per day for ewes with single lambs and 3.5 litres per day for ewes with twins. The number of lambs born per ewe also influences lactation requirements as a result of changes in the amount of pasture eaten by the lambs during the lactation period. For example, multiple born lambs are forced to eat pasture at an earlier age and will have a higher proportion of pasture in their diet in comparison to single lambs (Litherland et al., 2007, p. 12). This is because although ewes rearing multiple lambs have higher milk production, as this is shared between two or three lambs (in the case of twin and triplet litters respectively), total milk intake per lamb is lower (Geenty, 1979).

Pregnancy and lactation requirements are significant contributors to overall energy demands. Therefore, changes in the number of lambs born will impact on total feed demand. However, as these extra energy requirements are 'marginal' and are linked to production, increased pregnancy and lactation requirements may have little influence on the overall feed conversion efficiency of the sheep production system. Nonetheless, pregnancy and lactation requirements should have an influence on the seasonality of feed demand. This is due to the seasonal nature of these energy demands. Unlike maintenance energy demands, pregnancy and lactation requirements are for a defined period of time. For example, the average length of gestation for sheep is 150 days (Trafford & Trafford, 2011, p. A182) and weaning normally occurs within 12 weeks after the date of lambing (Litherland et al., 2007). Also, because pregnancy requirements are exponential in relation to time (Freer et al., 2007, p. 32), this means that the majority of pregnancy and lactation requirements fall within a period of approximately 130 days. For a given number of ewes, increasing reproductive performance could therefore be an important strategy to alter seasonal feed demands.

The effect of lambing percentage on average birth weight:

The number of lambs born per ewe has a negative relationship with lamb birth weight. From a total of 5,571 lambs born to Romney, Finn cross Romney, East Friesian cross Romney and Poll Dorset cross Romney ewes, Thomson, Muir, and Smith (2004) found that lambs from larger litters were smaller at birth, with on average a 1 kg disadvantage for every additional lamb. This is similar to the findings reported by Hinch et al. (1985) and Everett-Hincks, Dodds, and Wilson (2007). Lamb birth weight has important consequences for the timing of feed demands because if lambs are smaller at birth, this means that they will reach slaughter weights later. Larger litter sizes will therefore increase feed demands later in the season.

The effect of lambing percentage on lamb survival:

The number of lambs per ewe also influences feed conversion efficiency and the seasonality of feed demand as a result of lower lamb survival rates in twins and triplets (Table 3.1). This is due to the

Table 3.1 Lamb survival data in New Zealand in relation to birth rank

Author & Date	No. of lambs	-----------Birth Rank------------ Singles	Twins	Triplets
(Dalton, Knight, & Johnson, 1980)	10,049	83%	73%	
(Rohloff, Davis, & Hinch, 1982)	8,700	91%	93%	82%
(Hinch et al., 1985)	3,849	93%	82%	65%
(Hinch et al., 1985)	1,492	86%	76%	50%
(Hinch et al., 1985)	1,584	89%	85%	50%
(Kenyon, Morris, & McCutcheon, 2002)	1,030	83%	80%	59%
(Everett-Hincks, 2004)	~4,000	89%	94%	78%
(Thomson et al., 2004)	5,571	91%	90%	77%
(Muir & Thomson, 2009)	5,449	88%	86%	70%
MEAN (non weighted)		88%	84%	66%

higher risk of starvation/exposure (West, Bruere, & Ridler, 2009, p. 86) and is a consequence of lower birth weights. With lower rates of lamb survival, the number of lambs slaughtered per lamb born will decrease and this will reduce the potential meat output and lower feed conversion efficiency. With higher death rates, feed demand per lamb born will also be reduced later in the season, thus impacting on the seasonality of feed demands.

<u>The effect of lambing percentage on average lamb growth rate:</u>

Increasing the number of lambs per ewe will also impact on the whole-of-flock average lamb growth rate due to the lower growth rate of twin and triplet born lambs. For example, Thomson et al. (2004) found that mean lamb weaning weight for single lambs was 33.9 kg. This is in comparison to 29.5 kg for twins and 26.8 kg for triplets. Such differences in growth rates are explained through differences in milk intake per lamb and lower birth weights of multiple lambs (Geenty, 1979; Litherland et al., 2007; Peart, 1967). The rate of growth has important effects on the timing of feed demand and on feed conversion efficiency due to its effect on the timing of lamb slaughter, feed demands per day and total maintenance energy costs per lamb.

<u>The effect of lambing percentage on liveweight change:</u>

Due to the large demands of energy during this time, ewes bearing two or more lambs are often incapable of physically consuming the feed energy required during pregnancy and early lactation. Therefore, to support the feed demands of their lambs, ewes rearing twin or triplet lambs will utilise their own body reserves and will often lose liveweight and condition during late pregnancy and early lactation (Kerr, 2010, p. 23; Litherland et al., 2007, p. 1; Nicol & Brookes, 2007). Liveweight and condition must then be regained prior to the following mating to avoid penalties in reproductive performance (Allison & Kelly, 1978; Kenyon, Morel, & Morris, 2004; Rutherford et al., 2003). This fluctuation in liveweight impacts on feed conversion efficiency due to the imbalance in energy costs associated with gaining and losing liveweight. For example, each kg of liveweight lost provides approximately 30 MJME, but 55 MJME is required for each kg of liveweight gain (Nicol & Brookes, 2007). Thus, there is a 25 MJME/kg liveweight net requirement for weight that is lost and then regained. Therefore, increasing the number of lambs born per ewe will increase liveweight loss, leading to an increase in total energy requirements and a reduction in feed conversion efficiency when considered in isolation from other factors within the system. Ewe liveweight loss will also influence the timing of feed demands. There will be reduced energy demands during late pregnancy and early lactation as weight is lost, but there will be increased energy demands in the second half of lactation and over the period from weaning to mating as weight is regained.

The net effect of lambing percentage on feed conversion efficiency and the seasonality of feed demand:

There are many ways in which the number of lambs born per ewe influences feed conversion efficiency, both positively and negatively. Without objective and systemic analysis it is therefore difficult to predict the extent of change in whole-of-system feed conversion as a result in changes in the number of lambs born per ewe. Starting at low litter sizes, the maternal overhead costs per unit of output are high, and therefore, as litter size increases, and the overhead costs are spread across more output, overall feed conversion efficiency of the system should improve. However, due to the effect of higher pregnancy and lactation requirements, reduced lamb survival rates and slower growth rates, increases in feed conversion efficiency should occur at a diminishing rate. Large (1970) used experiments to estimate how the number of lambs born per ewe impacts on the weight of carcass produced per 100 units of Digestible Organic Matter (DOM) consumed. In these experiments, it was found the ewes rearing twin lambs had a 37.2% gain in efficiency in comparison to ewes rearing singles, while ewes rearing triplets had a 58.8% gain in efficiency. Although these experiments demonstrate high lambing percentages result in improved feed conversion efficiency, these experiments are based on indoor cage trials and exclude many of the factors that negatively influence feed conversion efficiency within a pastoral grazing flock. For example, in the study, all the lambs had equal birth weight and all lambs survived to slaughter. As a result, the effect on feed conversion efficiency is likely to be overestimated. Also, this experiment measured feed conversion efficiency against individual ewes. In reality, a flock will have different proportions of ewes in each birth rank (Amer et al., 1999), and therefore the results reported by Large (1970) do not represent a typical farming situation. Consistent with Large (1970), Vipond (2011) also states that increasing the litter size of ewes from one lamb to two lambs per ewe per year reduces the ME required per kg of carcass output by around 40%. However, there is no information on how this is calculated.

In relation to the seasonality of feed demand, the number of lambs born per ewe also has a complex effect. While at a component level it is easy to understand how the number of lambs born might influence the timing of feed demands, there is a lack of research that specifically calculates energy demands for the whole sheep flock throughout the year.

3.3 Lamb Growth Rate

A second key parameter of the sheep livestock system is the rate of lamb growth (liveweight gain) from birth to slaughter. In New Zealand, the daily growth rate of lambs averages approximately 150 g/day (Kerr, 2010, p. 7). However, growth rates of over 400 g/day are achievable (Kerr, 2010, p. 7). Important factors that influence lamb growth rate include genetics, nutrition and parasite control and are discussed in detail in *400 plus- A guide to improved lamb growth* (Kerr, 2010).

As analysed from a component basis, lamb growth rate is important for feed conversion efficiency and the seasonality of feed demand. First, faster lamb growth means that lambs will reach target slaughter weight sooner and require higher energy requirements per day (Table 3.2). However, faster lamb growth rates will also reduce the amount of feed required for maintenance due to the reduced time on-farm. As a result, increasing lamb growth rates will reduce the total amount of feed required per lamb to reach a given liveweight. For example, based on the data given by Geenty (1995), the amount of liveweight gain per total feed consumed per lamb growing from 24 kg to 34 kg is halved when lamb growth rates increase from 100 g/day to 400 g/day (Table 3.2).

Table 3.2 Feed consumed for different lamb growth rates after weaning (adapted from Geenty, 1995)

	Lamb growth rate (g/day) from 24 kg to 34 kg			
	100	200	300	400
Feed requirement (MJME/day)*	12.6	15.8	20.0	25.2
Days to target weight (34 kg)	100	50	33	25
Total feed consumed (MJME)	1,260	790	660	630
Liveweight Gain/Feed Consumed (g/MJME)	7.9	12.6	15.1	15.8

*Assuming M/D value is 10.5 MJME/kg DM

On this basis, many authors conclude that improved growth rates will lead to improved feed conversion efficiency of the system (Geenty, 1995; Kerr, 2010, p. 7; Large, 1970; Wallace, 1955). However, lamb growth is not constant across a flock and will vary in relation to birth rank, sex, and dam age (Muir, Smith, Wallace, Fugle, & Bown, 2000). Lamb growth rates will also vary in relation to age and the stage of maturity (Fitzhugh, 1976; Owens, Dubeski, & Hanson, 1993). This means that in terms of the sheep system as a whole, it is important to consider the proportions of lambs in each category and their relative growth rates.

3.4 Ewe Size

A third key parameter of the sheep livestock system is mature ewe liveweight or ewe size. Mature liveweight can vary significantly between breeds. For example, Merino ewes are approximately 55 kg at maturity, while Dorper ewes reach up to 90 kg (Meadows, 2008, p. 113). There is also considerable variation in mature liveweight within a particular breed. For example, Meadows (2008, p. 143) records that Romney ewes vary in liveweight from 45 kg to 65 kg. Ewe size has two important influences on feed conversion efficiency and the seasonality of feed demand.

The first influence is a result of the relationship between ewe size and maintenance energy requirement. For example, Nicol and Brookes (2007, p. 153) estimate that every extra 10 kg of liveweight increases maintenance energy requirements by 1.0 to 1.5 MJME/day. Smaller ewes therefore allow increased stocking density and higher productivity per unit of feed input. This was shown by Rutherford, Nicol and Logan (2003) who found that, for the same amount of feed, 14% more 60 kg ewes could be run in comparison to 70 kg ewes. When stocked at the same weight of ewe/ha, these small-framed ewes weaned 15% more lambs/ha, and produced 13% more lamb meat/ha. Similarly, in an on-farm experiment in Australia involving 360 Border Leicester x Merino ewes, Curll, Davidson, and Freer (1975) calculated that over 210 days (from four weeks before the start of mating to four weeks after the start of lambing) ewes that were 45 kg at the start of mating could produce 0.202 kg meat/kg DOM, which was double the total lamb production for ewes that were 57 kg at the date of mating.

The second influence is that ewe size affects the rate and composition of liveweight gain in growing lambs (Fitzhugh, 1976; Owens et al., 1993). For example, animals with lower mature liveweights will have higher concentrations of fat at lower liveweights and at an earlier age. Conversely, large sheep will be leaner at an earlier age (Nicol & Brookes, 2007, p. 153). This is important because the deposition of lean tissue requires considerably less energy in comparison to fat (Kerr, 2010, p. 69). For example, Nicol and Brookes (2007, p. 156) calculate that a 35 kg ewe lamb with a mature liveweight of 60 kg has an energy requirement for growth that is 1.0 MJME greater per 100 g liveweight gain than a 35 kg ewe lamb with a mature liveweight of 80 kg. Assuming that the mature size of lambs is correlated with the mature size of their dams, smaller ewes will therefore increase energy demands in growing lambs as a result of higher rates of fat deposition relative to protein.

3.5 Target Carcass Weight

Target carcass weight is another key parameter of the sheep meat livestock production system. This is the weight when lambs are slaughtered and is chosen by management, either indirectly by slaughtering all lambs at a fixed date, or directly through regular drafting of lambs and selecting lambs based on their liveweight and their estimated dressing-out percentage. In 2013, the average carcass weight of slaughtered lambs in New Zealand was 18 kg (Statistics New Zealand, 2014). However, based on their meat schedules, meat processors such as Silver Fern Farms and Alliance accept lambs anywhere from 9.1 kg to 30 kg carcass weight (Interest.co.nz, 2015).

Target carcass weight influences feed conversion efficiency due to the effect on maternal feed energy costs per kg carcass. For example, the energy required for the ewe (for maintenance, lactation, pregnancy, and liveweight gain) is the same independent of the weight in which lambs are slaughtered and therefore increasing carcass weights will reduce the maternal feed energy costs per kg meat carcass. This has a positive influence on feed conversion efficiency. However, as slaughter weights become closer to the mature liveweight of lambs, the energy costs associated with liveweight gain will become progressively more expensive and the rate of liveweight gain will be slower (Fitzhugh, 1976). For example, Large (1970), calculated that the feed conversion efficiency (measured as the weight of carcass produced per 100 units of digestible organic matter consumed) of Suffolk × Kerry Hill lambs would increase from approximately 5 units to 8 units when mean carcass weight was increased from 10 kg to approximately 18 kg. However, Large (1970) also showed that the relative effect on feed conversion efficiency reduces with increased carcass weight and beyond 18 kg carcass weight feed conversion efficiency actually declines.

Target carcass weight is also important in regard to the timing of feed energy demand. This is because carcass weight is a major factor which determines how long animals remain on-farm. For example, if target carcass weights are low, lambs can be sold at or shortly after weaning[3]. Low target carcass weights will therefore result in a large reduction in stock numbers near weaning date and consequently significantly reduce feed demands in the last part of the season. In comparison, if target carcass weights are high, then lambs may need to be retained on-farm for six months or more depending on lamb growth rate. This will mean that feed demand will remain higher for longer in the season.

[3] In some cases lambs with faster growth rates, such as single lambs, may even be able to be sold prior to weaning.

3.6 Hogget Lambing

Sheep have the potential to be mated from six to nine months of age as “hoggets” (West et al., 2009, p. 43). However, in contrast to 2-tooth and MA ewes, hoggets are not always mated. For example, in 2013 only 30% of ewe hoggets were put to the ram (Statistics New Zealand, 2014). Hogget lambing, defined as the number of lambs (from hogget dams) tailed per total hogget at mating date, is a further key parameter of the sheep livestock system. While hogget lambing is affected by the proportion of total hoggets mated, it is also a function of the reproductive performance per hogget mated.

When hoggets are mated and have a lamb, it means that feed overhead costs of rearing the hogget can be spread over more output and this therefore influences feed conversion efficiency (Wallace, 1955). In relation to the timing of feed demand, hogget lambing will have several impacts. First, mated hoggets must be heavier than otherwise necessary for non-mated hoggets. This is because age of puberty in hoggets is liveweight related and heavier hogget liveweights are required to ensure adequate conception rates (Geenty, 1997, p. 36). Kenyon (2012, p. 9) suggests a minimum mating weight of 42 kg for hoggets that have a mature liveweight of 65 kg. To achieve higher mating weights, growth rates of replacement ewe lambs must be greater. Therefore, by mating hoggets, feed demand will be increased prior to mating as a result of higher energy requirements for liveweight gain. The increased demand continues through early and mid-pregnancy. However, during late pregnancy and early lactation the feed demand of mated hoggets is constrained by their inability to make major weight gains during these periods (Kenyon, 2012, p. 20). Hogget lambing will also increase total energy requirements for pregnancy and lactation and will increase feed demands after weaning due to the greater number of lambs born.

3.7 Age of Ewe Culling

Johnston (1983, p. 2) reports that the natural lifetime of ewes is 8-10 years. However, sheep are often sold or culled cast-for-age prior to this (McGregor, 1979, p. 3; Trafford & Trafford, 2011, p. O12). The age at which ewes are culled is another key parameter of the sheep livestock system. Cull age impacts on feed conversion efficiency and the seasonality of feed demand as a result of its effect on the number of replacement ewe lambs that are needed per year, reproductive performance, mortality rate, and lamb birth weight and survival.

<u>The effect of age of ewe culling on the number of replacements:</u>

In a steady-state self-replacing flock, cull age determines the relative number of ewes in each age group (Byrne, 1967). For example, delaying the age of ewe culling will increase the number of old ewes in the flock and decrease the number ewe lamb replacements, hoggets and 2-tooth ewes. This is important in terms of feed conversion efficiency as "the feed cost of rearing female stock for breeding is one of the important overhead charges in meat production" (Wallace, 1955, p. 10). If ewes are kept longer prior to culling then this will reduce the overall maintenance energy costs of the sheep flock due to the fact that fewer replacements must be retained. The reduced number of ewe lambs required for ewe replacements will also allow more lambs to be slaughtered thus increasing meat output and feed conversion efficiency.

The effect of the age of ewe culling on average lambing percentage:

Age of culling also influences feed conversion efficiency and the seasonality of feed demand as a result of the relationship between ewe age and reproductive performance. With the exception of very old ewes, reproductive performance will increase with age. This is due to lower embryonic mortality (West et al., 2009, p. 57) and higher fertility and ovulation rates in comparison with younger ewes (Dickerson & Glimp, 1975; West et al., 2009, p. 49). For example, Thomson et al. (2004) report that 2-tooth ewes had a mean litter size of 1.55 while mixed-aged ewes had a mean litter size of 1.7. Higher reproductive performance will effect ewe maintenance requirement, pregnancy and lactation requirement, ewe liveweight loss, and will also impact on average lamb birth weight, survival and growth rate. The effect that these factors have on feed conversion efficiency and the seasonality of feed demand have previously been discussed in section 3.2.

The effect of the age of ewe culling on average mortality rate:

In addition to reproductive performance, ewe age also influences ewe mortality. As ewe age increases, so too does ewe mortality rates (Byrne, 1967; Hickey, 1960). Higher mortality rates will reduce the number of ewes that can be sold cast-for-age, thus reducing meat output and feed conversion efficiency. Additionally, if ewe deaths occur prior to lambing, it will also reduce the number of ewes that lamb. For example, despite higher reproductive performance per ewe lambing, Hickey (1960) found that the maximum number of lambs docked per ewe mated was attained at four years of age. This was due to the negative influence of higher death rates as age increased.

The effect of the age of ewe culling on average lamb birth weight:

Ewe age is also important due to its association with lamb birth weight. For example, lambs born to ewe hoggets are on average 1 kg to 1.5 kg lighter at birth and 3 kg to 5 kg lighter at weaning than those born to mature ewes (Kenyon, 2012, p. 30). Birth weight is also significantly lower in 2-tooth ewes in comparison to mixed-aged ewes (Thomson et al., 2004). Hight and Jury (1969) report mean birth weights of 4.8 kg for lambs born to 2-tooth ewes and 4.9 kg for lambs born to older ewes. Due to these influences, increases in cull age will also result in an increase in average lamb birth weight and consequently reduce the amount of time that lambs take to reach target slaughter weight.

The effect of the age of ewe culling on lamb survival rates:

Ewe age also impacts on lamb survival rates (Dalton et al., 1980; Hight & Jury, 1970; Knight, Lynch, Hall, & Hockey, 1988). For example, Thomson et al. (2004) found that more of the lambs born to 2-tooths were dead at tagging than the lambs born to mixed aged ewes (7.8% vs 4.0%). Likewise, Hickey (1960, p. 340) found that 12.4% of the lambs born to 2-tooth ewes died at some point between tailing and the attainment of age 1.5 years, compared with 7.6% of those born to ewes mated at the age of 5.5 years old. By increasing the average age of the flock, increasing cull age will therefore reduce neo-natal mortality of lambs and will consequently positively influence feed conversion efficiency. This is because increased lamb survival increases the number of lambs that can be sold which in turn reduces the overhead feed costs of the ewe per kg of lamb carcass sold. Also, because higher lamb survival rates increase feed demands (due to there being more lambs), cull age will also influence the seasonality of feed demand.

The net effect of the age of ewe culling on feed conversion efficiency and the seasonality of feed demand:

Cruickshank et al. (2008) modelled the effect of age of culling on the production efficiency of the sheep flock measured as the kg of methane output (CH4) per lamb sold. It was found that delaying culling by one year (i.e. culling ewes at 6 years rather than 5 years of age) decreased methane emissions by 6.5%. Nugent and Jenkins (1993) used a deterministic computer simulation model to estimate the effects of age of culling on biological efficiency defined as grams of empty body weight equivalent value of market lamb, cull ewe, and wool output (EBW) per kilogram input of total digestible nutrients (TDN). It was found that depending on precocity, EBW/TDN was highest when ewes were culled at four or five years of age. Similarly, using a linear programming model, McGregor (1979) found that ewes should be culled at five and six years of age, under irrigated and dry-land conditions respectively. Although these studies use different measures of feed conversion efficiency, they suggest that meat output per feed energy input may be optimised when ewes are culled around 6 years of age. However, none of the above studies investigate how the age of ewe culling will affect the timing of feed demands.

3.8 Death Rates

Death rates of both ewes and lambs are another important parameter of the sheep livestock system. As stated by Large (1976, p. 49), “those animals that die are a complete loss to the system and will reduce overall efficiency”. Timing of feed demands are also important as higher death rates will reduce feed demand later in the season. However, the higher death rate will require higher ewe replacement rates and consequently will increase whole of system feed demand.

3.9 Stocking Rate

There are different interpretations of what is meant by stocking rate. Here, stocking rate is defined as the number of animals per ha. While this is a common use of the expression, a more correct term for this meaning is stock density.

Stocking rate has an important effect on the output of meat per unit of feed input. For example, Figure 3.1 shows a model of the theoretical effect of stocking rate on per ha productivity. In this model, the relationship between stocking rate and per ha productivity has three phases. In the first phase, per ha performance increases rapidly as a result of more animals and increased production per head. Increased per head performance is the result of increases in pasture utilisation which result in increased pasture quality and subsequently allows for higher animal intake. For example Kerr (2010, p. 45) states that “if a farm is under-stocked, some pasture isn’t grazed and there’s waste and deterioration of quality through death and decay of the pasture”. In such situations increasing stocking rate will improve pasture quality and this will improve per head animal performance (A. Nicol, personal communication, April 29, 2010). In phase two, total production per ha continues to increase with increased stocking rate. However, as a result of greater competition between animals, individual animals have lower feed intakes and per head animal performance decreases. In phase three, with increased stocking rates, per animal performance collapses due to overgrazed pastures, reduced pasture production, and low intakes. This results in decreases in per ha performance as the feed costs of extra animals are high relative to the low per head performance.

Figure 3.1 Stocking rate by productivity model (A. Nicol, personal communication, April 29, 2010)

At the level of the farm system, the relationship with total output per ha means that stocking rate will have considerable impact on the efficiency of meat output per unit of feed input. However, although stocking rate is very important, determining the optimal number of animals run per ha presents a considerable challenge (Spedding et al., 1981, p. 232). This is because the optimal number of animals per ha will depend on the feed supply per unit area, the relative number of rams, hoggets and lambs per ewe and on the feed demands required to achieve specified per head performance levels. Therefore, although a key parameter of production, stocking rate is considered an output decision and should be calculated as a function of target performance levels of the system and feed supply.

It is also important to recognise that the effect of stocking rate on product output and feed efficiency is the result of complex pasture-animal interactions. For example, if stocking density is too great, the feed intake and performance of individual animals will reduce (Cosgrove & Edwards, 2007). While these factors are important, when analysed independent of farm feed supply, ewe numbers will have no effect on output per unit of feed energy demand. This is because, when pasture-animal interactions are ignored, increasing the size of the ewe flock will simply increase the scale of meat output in absolute terms. It will not increase the efficiency of production.

3.10 Mating Date

Mating date is one of the most important factors determining the timing of feed requirements of the livestock system (Kerr, 2010, p. 10). For example, the timing of pregnancy and lactation requirements and the feed requirements of lambs are determined by the date in which ewes are mated. However, when analysed at the level of the sheep livestock system, mating date will result in a seasonal shift in the feed demand profile rather than a change in the overall quantity of feed demand. For example, mating ewes two weeks later will shift absolute feed demands by two weeks. Feed demands relative to mating date will, however, remain the same. Also, assuming that mating date coincides with the breeding season (Montgomery, Scott, & Johnstone, 1988; Quinlivan & Martin, 1971), mating date will not impact on feed conversion efficiency at the level of the sheep livestock system. Therefore, in terms of farm planning, the date of mating needs to be considered only after the seasonal profile of feed demand is calculated and the expected profile of feed supply is known.

3.11 Residual Feed Intake

At the level of the individual animal, energy requirements required to obtain a certain level of production vary from animal to animal. For example, residual feed intake (RFI) is a measure of feed eaten relative to predicted feed intake and is independent of production traits such as growth rate and animal size (Koch, Swiger, Chambers, & Gregory, 1963; Waghorn & Hegarty, 2011). The bases for differences in RFI have been ascribed to the physiology and biochemistry associated with digestion, energy capture (i.e., as ATP) and energy utilisation and are genetically determined (Herd & Arthur, 2009). RFI has been shown to be moderately heritable (Korver, Van Eekelen, Vos, Nieuwhof, & Van Arendonk, 1991; McNaughton & Pryce, 2007) and thus there is the potential to improve system feed conversion efficiency through the genetic selection and breeding of lower RFI animals. However, while analysis using the GrassGrow model by Alcock and Hegarty (2011) suggests that a RFI can have important implications for system-level feed efficiency, RFI is not a directly observable trait as it relates to within-animal biological processes rather than system-level performance levels. Consequently, RFI has been excluded from analysis in this study.

3.12 Conclusion (The Knowledge Gap)

While there have been many New Zealand and international studies that have evaluated the biological efficiency of alternative animal performance levels and alternative livestock strategies (for example Large, 1970; Spedding et al., 1981; Geenty, 1995; Cruickshank et al. 2008), these studies have typically focused on a sub-system level of analysis and have ignored some important system interactions. Consequently, recommendations from these component studies do not readily translate into improved system performance. For example, as suggested by McCall et al. (1994, p. 418) “if all the 5 and 10% gains in production identified by component research were additive, pastoral production could probably be shown to be at least 100% greater than currently achieved”. Further, no New Zealand studies have evaluated the interactions between FCE and seasonality of demand. Therefore the research gap is that there is a lack of quantitative information on how key livestock parameters such as ewe lambing percentage, lamb growth rate, ewe size, target carcass weight, hogget lambing, age of ewe culling, and mortality rate impact on both whole-of-system feed conversion efficiency and feed demand seasonality.

The following chapter explains the methodology and assumptions used to construct the whole-of-system demand-driven model of the sheep livestock system which is used to address this knowledge gap.

Chapter 4

Model Construction

4.1 Introduction

In order to answer the research questions, a demand-driven deterministic steady-state enterprise level model of a sheep meat livestock production system was developed in Microsoft Excel™ and was solved using linear programming. In relation to a baseline scenario, model experimentation using post-optimality analysis and parametric programming was then undertaken to investigate how lambing percentage, lamb growth rate, carcass weight, ewe size, hogget lambing, age of ewe culling and mortality rate impact on whole-of-system feed conversion efficiency and feed demand seasonality.

The purpose of this chapter is to describe the modelling technique that was used to develop the biological livestock model used in this research and to outline the assumptions used in the baseline scenario. The methods and assumptions for the calculation of economic outputs are described in Chapter 8.

4.2 The Biological Model

In this research, the sheep livestock model was constructed to represent a steady-state, self-contained breeding-finishing sheep production system (at the livestock sub-level of the farm system) and was set up in reference to the annual breeding cycle of ewes. First, using Microsoft Excel™ (2010), weekly feed demands were simulated in megajoules of metabolisable energy (MJME) for each class of livestock and performance level. Feed demand was expressed in terms of energy because, in pastoral systems, energy is typically the most limiting factor (Freer et al., 2007, p. 1; Nicol & Brookes, 2007; Sykes, 1980). This is in line with other models of pasture-based farming systems (Anderson & Ridler, 2010; Doole & Romera, 2013; McCall & Clark, 1999). Equations used to calculate individual energy requirements were taken from the generalised equations adopted by the Australian Standing Committee on Agriculture (Freer et al., 2007; SCA, 1990) and were calculated using the factorial approach with total energy requirement being the sum of the MJME required for maintenance, liveweight gain (or loss), pregnancy, and the ewe and lamb lactation requirement. In contrast with other livestock models (Cruickshank et al., 2008; Ludemann, 2009; Woodford, 1997, pp. 161-185), energy demands were calculated on a weekly basis rather than on a monthly basis. This was because a key purpose of this research was to investigate the relationship between the sheep livestock system and the timing of feed demands. A shorter time period was chosen as this increases the accuracy in reporting feed demands and reduces the chance of unseen changes occurring within a given period (McGregor, 1979, p. 56).

It is of importance to emphasise that, in this research, simulated feed demands represented the amount of feed required to be eaten by each animal to achieve specified production targets and did not represent the amount of feed required to be supplied to the animal (the model did not account for feed utilisation or wastage). Therefore, the model is not a farm level model, but rather, is a livestock level sub-model of the farm system.

The simulation outputs then became the inputs to the linear programming model which was solved using the Microsoft Excel™ add-in, Solver™, developed by Frontline Systems. As described by Anderson et al. (2013, p. 17), linear programming is a mathematical procedure that maximises or minimises a linear function subject to constraints that limit the degree to which the object can be pursued. A detailed description of linear programming was given in section 2.10. In this research, the use of linear programming was primarily due to its usefulness as a calculator and provided the framework for determination of overall flock structure, incorporation of component interactions, and assessment of whole-of-system feed demand seasonality.

In this research, the choice of constructing the linear programming problem in matrix form within Microsoft Excel™ and then solving using Solver™ was made due to the familiarity of the author with these software programs. In making this decision, it was acknowledged that, with large linear programming models, it is preferable to construct the mathematical program using modern matrix generating programming languages such as the General Algebraic Modelling System (GAMS) software language (www.gams.com). However, although software languages such as GAMS make it faster and easier to construct and redefine large mathematical programs, this approach would have required considerable investment in time to learn.

In the linear programming model, the objective function was maximisation of total meat carcass (lamb plus ewe mutton). Model outputs included flock structure, weekly and seasonal feed demand, and feed conversion efficiency measured as the grams of meat carcass produced per year per MJME (g carcass/MJME). In this study, meat production was used as the measure of product output as this is a key output of the sheep production system and was the focus of this research. Weight of carcass refers to cold carcass weight and refers to the cold weight of a carcass following slaughter and after removal of the pelt, head, feet, internal organs, mammary systems, internal fats, tail, aorta, and neck (New Zealand Meat Classification Authority, 2004). Cold carcass weight was chosen as the unit of output as this represents a “convenient marketable end point for meat” (Large, 1970) and forms the basis of meat payment for farmers in New Zealand (New Zealand Meat Classification Authority, 2004). The conversion of carcass weight to lean meat depends on a number of factors but as a way of example, from a total of 837 lambs, Kirton, Duganzich, Feist, Bennett, and Woods (1985) calculated that lean meat yield was 57.2%. In the model, lamb and ewe mutton carcass output were measured separately as well as combined.

Rather than being linked to an absolute date, feed demand was calculated per week relative to ewe mating date. This was done to increase the generalizability and adaptability of the model findings. For example, feed demand profiles can be compared across farms with different ewe mating dates. Although calculated in weeks, to increase the simplicity of reporting, the seasonality of feed demand was also reported in relation to macro periods of the year and relate to key management periods within the annual breeding cycle of ewes, i.e. pregnancy (weeks 1-21), lactation (weeks 22-33) and post-weaning (weeks 34-52).

The linear programming framework was set up within Excel™ in matrix form according to the framework for modelling livestock enterprises as described in Chapter 6 of Dent, Harrison and Woodford (1986). However, in contrast with supply driven models where animal numbers and their performance are determined by feed supply, similar to the approach used by Woodford (1997, pp. 161-185), total animal numbers and feed demand seasonality were determined endogenously within the model and were model outputs. To bound the model, total system feed demand was arbitrarily constrained to 10 million MJME which, under New Zealand conditions, approximates the feed supplied from about 100 hectares of pastoral land[4]. As noted by Woodford (1997, p. 162), the use of 10 million MJME is arbitrary in that "alternative numbers would simply produce scale versions of the same outcomes".

It is useful to emphasise two inherent assumptions that result from the use of linear programming. First, linear programming models assume that the transformation relationships linking inputs and outputs are linear (Hillier & Lieberman, 2005, p. 38). However, it is important to note that while this linearity assumption means that individual animal requirements are scaled arithmetically to flock levels, this does not constrain representation of within-animal non-linear biological complexity. For example, the equations within Excel™ were not linear and incorporate exponential and logarithmic biological relationships as appropriate. Rather, the linearity assumption in linear programming simply means that as the number of animals in a class increases or decreases, then the overall feed requirement also increases or decreases proportionally. In other words, "doubling the number of animals in a particular category will also double the total feed requirement" (Woodford, 1997, p.

[4] E.g. 10 million MJME is equivalent to 100 ha producing 9,500 kg DM of pasture per year that has an M/D value of 10.5 MJME/kg DM

163). The implication of this is that it is assumed that there are no economies of scale in relation to feed conversion efficiency.

The second inherent assumption worth emphasising is that linear programming models are deterministic (Dent et al., 1986, p. 49). This means that “without major modification to the analytical framework, it is not possible to capture the stochastic nature of the bio-physical world” (Woodford, 1997, p. 163). Consequently, the findings obtained from the model are aimed as a guide for strategy rather than for day to day use.

The deterministic approach also follows naturally from the demand-driven paradigm of the research. This is because the animal feed demand equations are traditionally reported as being deterministic (Freer et al., 2007; SCA, 1990). Where models are stochastic, this is achieved by building stochasticity in the feed supply but the feed requirement equations are accepted as being deterministic (Cacho, Bywater, & Dillon, 1999). Therefore, as this research is demand-driven (and not influenced by feed input assumptions), the output is deterministic because the demand equations are reported as deterministic equations.

A simplified version of the biological linear programming tableau is presented in Figure 4.1. The baseline linear programming model had 176 activities. There were five breeding flock activities (sire ram, replacement ewe lamb, hogget, 2-tooth ewe, and MA ewe activities), two hogget mating activities (mated and not mated activities), four hogget reproductive performance activities for those hoggets that were mated (dry, die pre-lambing, single, and twin activities), and 10 reproductive performance activities for 2-tooth and MA ewes (dry, die pre-lambing, single, twin, and triplet activities). There were four fate activities for unmated hoggets (die early, die late, culled, and survive activities), two fate activities for mated but dry hoggets (culled and not culled activities), three fate activities for mated but dry hoggets that were not culled (die, culled, and survive activities), and three activities each for hoggets that had either single or twin lambs (die, culled and survive activities).There were 18 fate activities for 2-tooth and MA ewes that lambed (die, culled and survive activities for single, twin and triplet bearing ewes) and were four lamb activities for hogget dams (single and twin activities for ewe and ram lambs). There were 12 lamb activities for 2-tooth and MA ewe dams (single, twin and triplet ewe and ram lamb activities for both 2-tooth and MA ewes). There were also 12 lamb fate activities for lambs born to hogget dams (born dead, die and sale activities for single and twin ewe and ram lambs), 18 lamb fate activities for lambs born to 2-tooth dams (born dead, die and sale activities for single, twin, and triplet ewe and ram lambs), and 22 lamb fate activities for lambs born to MA ewes (born dead, die and sale activities for single, twin and triplet ram lambs and triplet ewe lambs; born dead, die and survive activities for single and twin ewe lambs; and replacement and sale activities for single and twin ewe lambs that survive). There was also one activity for total lambs sold, 52 feed demand activities (one for each week) and one total feed demand activity.

There were three tie rows linking breeding females to the next age group (ewe lamb replacement, hogget, 2-tooth ewe and MA ewe categories), two tie rows linking hoggets to mating activities and 14 tie rows linking mated hoggets and ewes to reproduction activities, 33 tie rows linking reproduction activities to ewe and hogget fate activities, 16 tie rows linking lambs from hoggets and ewes to sex categories and 50 tie rows linking ewe and ram lambs to fate activities. In addition, one tie row linked ewes to rams, one tie row linked single and twin ewe lamb replacement activities to total ewe lamb replacements, and one tie row linked lamb fate activities to total lambs sold. There were also 52 tie rows linking animals to whole-of-system weekly feed demands, one tie row linking weekly feed demand to total annual feed demand and one tie row linking total annual feed demand to maximum feed demand.

Constraints		Max MJME	Relation ship	MJME Demand	Animal Activities	Feed Demand 1	2	.	.	.	52	Total
Max MJME		10,000,000	≥	[ ]								1
Feed Demand:	Week 1				Weekly feed requirement in MJME for each animal category based on liveweight and performance assumptions	-1						
	Week 2						-1					
	.							.				
	.								.			
	.									.		
	Week 52										-1	
	Total					1	1	.	.	.	1	-1
Flock Structure Ties					Coefficients Linking Animal Activities							
Lambing Performance Ties												
Ewe and Lamb Mortality												
Lambs Sold												
Ewes and Hoggets Sold												
Objective Function				Total Kg	Carcass Weight of Animals Sold							

Figure 4.1 Schematic representation of the biological linear programming tableau

While individual livestock parameters used in this research are within the bounds of known technical feasibility, values are based on the deliberate selection of 'essential and typical' units (Davidson & Tolich, 2003, p. 119). As such, this research does not purport to represent a specific farm situation. Rather, this research is normative and the model's predicted outcomes is at the level of the system and is based on specified and interacting variables. This study can therefore be considered generic and has relevance across all physical environments. However, it cannot provide optimal solutions for specific environments, each of which have their own unique feed supply conditions together with product pricing relationships which will change over time. In Chapter 8, it is shown how the model can be adapted to evaluate outcomes for different feed environments and economic conditions.

4.3 Assumptions

Key assumptions required in the development of the baseline linear programming model include the timing of activities, replacement rate, ewe culling, mortality rate and mating ratios. Assumptions also include reproductive performance, lamb survival, and individual liveweights and energy requirements.

4.3.1 Timing of Activities

Lambing

In the model, the gestation period of pregnant ewes and hoggets was assumed to be the average gestation period of sheep reported by Johnston (1983, p. 2) and McMeekan (1960, p. 20) with lambing date being 147 days (21 weeks) after the date of mating. In the model, the date of mating for MA and 2-tooth ewes is at the start of week one. For hoggets, the date of mating was four weeks after ewe mating. This was to account for the fact that, in many breeds, the onset of reproductive activity in hoggets is later than mature ewes (Kenyon, 2012, p. 6; West et al., 2009, p. 43).

In the model, mating date was assumed to be the mean mating date and all ewes were assumed to conceive (and lamb) simultaneously. Therefore, within-flock variation in conception and lambing date has been ignored.

Weaning

For MA ewes, a 12 week weaning age has been chosen for the base model. This is a common date for weaning (Cruickshank et al., 2008; Shadbolt, 1982; Thomson et al., 2004; Woodford & Nicol, 2005). To give hoggets a chance of getting up to target weights by 2-tooth mating, Kenyon (2012, p. 31) recommends that lambs born to hoggets should be weaned earlier than lambs born to mature ewes. Consequently, in the base model, hogget weaning was assumed to be 10 weeks after lambing.

Sales dates

Rather than being based on a fixed date, in the model, lambs were sold when they reached target slaughter weights. The timing of lamb sales was therefore a function of target carcass weight as well as lamb birth weight and growth rate.

4.3.2 Replacements

In the model, there was no provision for replacement breeding ewes to be sourced from off-farm. Rather, all replacements were assumed to be sourced from retained ewe lambs. It was also assumed that only lambs from MA ewes would be chosen as replacements[5]. Replacements were also 'selected' from those lambs that survived. The number of ewe lambs retained was determined by the number of hoggets required to maintain a steady-state flock and the ratio of single lambs to twin lambs chosen for replacements was determined by the model. The model selected the option that allowed for the highest total meat production.

4.3.3 Culling

In the model, ewes were culled for three reasons:

1. First, with the exception of ewe hoggets, all ewes that failed to lamb (dry ewes) were culled at pregnancy scanning. Based on the recommendations reported in Trafford and Trafford (2011, p. A13), this was assumed to be 11 weeks after the start of mating.

2. Ewes were also culled for serious faults such as poor feet, teeth, or udder. The proportion of ewes culled for serious faults was based on the assuptions used by Cruickshank, Thomson, and Muir (2008) and was related to age (Table 4.1).

Table 4.1. Percentage of ewes within each age group culled for serious faults

Age Group	% of age group Culled
Hoggets	0.00
2-tooth ewes	0.15
4-tooth ewes	0.70
6-tooth ewes	1.20
4yr ewes	2.00
5yr ewes	2.50
6yr ewes+	3.00

[5] Appendix A outlines some technical aspects on modelling ewe replacements within a steady-state linear programming framework

3. Last, ewes were culled for age. In the base model, ewes were culled after six lambings as a ewe at 7.3 years of age.

Ewes with serious faults and cast-for-age ewes were culled two weeks after weaning.

4.3.4 Ewe Mortality

In the base model, mortality rates for breeding females were similar to the mortality rates observed in the Poukawa ewe longevity trials (Cruickshank et al., 2008). It was assumed that the mortality rate of MA ewes was 3% with the exception of aged ewes (7 years and older at the date of mating), which were assumed to have a mortality rate of 4.5%. The death rate of hoggets was assumed at ¼ the mortality rate of MA ewes at 0.8% and the 2-tooth mortality rate was assumed at ½ the mortality rate of MA ewes at 1.5%. In relation to the timing of deaths, it was assumed that 50% of deaths were to occur one week prior to lambing and the remaining 50% of deaths were to occur two weeks after weaning (the date of culling). To avoid understating the energy costs of those ewes that died prior to lambing, the energy cost of pregnancy (of a single lamb) were attributed to such ewes.

4.3.5 Mating Ratios

In the model, the number of sire rams was determined as a function of ewe numbers based on recommended mating ratios. For ewes, a mating ratio of 1:100 was used. This was consistent with that suggested by West et al. (2009, p. 54), Geenty (1997, p. 51), and Trafford and Trafford (2011, p. A12). Ewe hoggets do not actively seek out the ram, so it is recommended that they be mated at higher ratios than used for mature ewes (West et al., 2009, p. 44). Consequently, for hoggets, a mating ratio of 1:50 was used.

4.3.6 Dressing-out Percentage

In the model, the dressing-out percentage (DO%) was calculated by adapting the equation given by PGG Wrightson (2014, p. 24). This equation takes into account the fact that dressing-out percentage increases as liveweights increase (Kirton, Carter, Clarke, & Duganzich, 1984; Purchas, Stevens, & Familton, 1999, p. 27). For cull ewes, dressing-out percentage was estimated in relationship to liveweight using the equation:

$$\mathrm{DO\%} = \frac{(\mathrm{Lwt}\ \times 0.473 - 1.92) \times 1.045}{\mathrm{Lwt}} \times 100$$

Where:

$\mathrm{DO\%}$ = the dressing-out percentage, and
Lwt = Liveweight (kg)

For sale lambs, this equation was arranged so that dressing-out percentage was calculated in relation to target carcass weight and also adapted to allow for differences in dressing-out percentage as a result of sex (Kirton et al., 1984).

The dressing-out percentage of sale lambs was calculated using the equation:

$$\mathrm{DO\%} = \left(\left(\frac{\mathrm{Cwt}}{\frac{\left(\frac{\mathrm{Cwt}}{1.045}\right) + 1.92}{0.473}} \right) \times 100 \right) + \mathrm{A}$$

Where:

$\mathrm{DO\%} =$ Dressing-out percentage,
$\mathrm{Cwt} =$ Lamb carcass weight (kg), and
$\mathrm{A} =$ The adjustment for gender. For ram lambs this is -1% and for ewe lambs this is +1.3%.

In the base model, the average dressing-out percentage was 46.2% for cull ewes and 45.6% for cull hoggets. For sale lambs the dressing-out percentage was 45.8% for ewe lambs and 43.5% for ram lambs.

4.3.7 Reproductive Performance

In the base model, the reproductive performance of ewes (aged 2-tooth and older) was such that the overall lambing percentage (number of lambs tailed per ewe mated) was 120%. This is similar to the New Zealand national average for 2013 (Statistics New Zealand, 2014).

In the model, all ewes were mated. The number of lambs born per ewe mated was derived as a function of ewe deaths prior to lambing, the proportion of ewes that were dry (barren) and the number of lambs born per ewe lambing and was calculated in relationship with ewe age. The number of lambs tailed per ewe mated and the number of lambs sold (or kept for replacements) per ewe mated was a function of the number of lambs born per ewe mated and lamb survival rates (see section 4.3.9).

It was assumed that the death rate prior to lambing was equal to half the annual death rate per age group. For mixed aged ewes, the proportion of ewes that were dry at ewe scanning was assumed to be 4%. This is equal to the average dry rate observed from a total of 64 sheep flocks in New Zealand (Kelly, 1982). To account for the fact that younger ewes have lower fertility rates (Allison & Kelly, 1978; Thomson et al., 2004), in the base model, 2-tooth ewes had a slightly higher dry rate of 5%.

In the base model, litter size (lambs born per ewe lambing) was calculated in relation to ewe age and was from data from Thompson, Muir, and Smith (2004). It was assumed that prior to six years of age litter size increases with age. For ewes six years old and older, it was assumed that litter size decreases with age. The coefficient of correlation used to calculate the litter size of older ewes in relation to the litter size of 2-tooth ewes are shown in Table 4.2.

Table 4.2 Correlation coefficient of ewe litter size in relationship to 2-tooth ewes

Age @ mating	Correlation Coefficient
2-tooth Ewe	1
4-tooth Ewe	1.11
6-tooth Ewe	1.17
4yr Ewe	1.23
5yr Ewe	1.28
6yr Ewe	1.18
7yr Ewe	1.1
8yr Ewe	1.08
9yr Ewe	1.02
10yr Ewe	0.99

In the model, the proportion of ewes having single, twin, or triplet litters in relation to average litter size was calculated using the polynomial equations shown in Appendix B. These equations were derived in reference to the model of birth rank proportions used by Amer et al. (1999) which were in turn based on the whole flock observations of traditional New Zealand breeds made by Davis et al. (1983). It is assumed that up until an average litter size of 150%, twins substitute singles. When litter size was greater than 150% it was assumed that triplet lambs become increasingly prevalent (Figure 4.2). The maximum proportion of twinning ewes was 0.66 per ewe lambing.

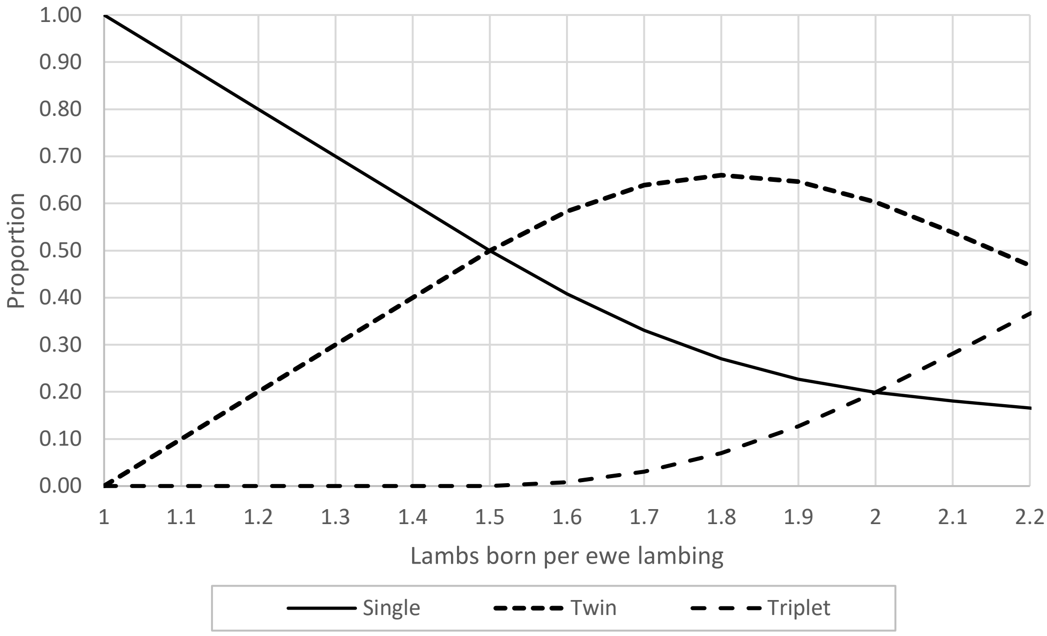


Figure 4.2 The proportion of ewes with single, twin and triplet litters per ewe lambing in relation to average litter size (the number of lambs born per ewe lambing)

4.3.8 Hogget Lambing

In the base model, it was assumed that all hoggets are mated and the reproductive performance of these hoggets was such that the number of lambs tailed per hogget mated was 60%. This is approximately the 2013 New Zealand average lamb tailing percentage per hogget mated (Statistics New Zealand, 2014) and was calculated assuming that the dry rate was 44% and that the number of lambs born per hogget lambing was 110%. The relationship between the proportion of hoggets with single and twin lambs to average litter size was assumed to be the same as for ewes. In the base model, 90% of the hoggets that lambed had single lambs and 10% had twins.

4.3.9 Lamb Survival

In the model, lamb deaths were grouped into one of two categories. Lambs either died at birth or during the lactation period. Data for lamb deaths at birth and from birth to weaning were from Cruickshank, Thomson, and Muir (2008) (Table 4.3). To be conservative with feed demand estimates, in the base model, the energy costs of pregnancy were attributed to those lambs born dead. As the date of lamb deaths during lactation was unknown, it was assumed that lamb deaths occurred six weeks after the mean lambing date. For lambs born to ewes, this was half way between lambing and weaning. Also, for the lambs that died during the lactation period, the energy costs of lactation were attributed to these lambs up to and including the date on which they died.

Table 4.3 Lamb mortalities by age at death and birth rank (Cruickshank et al., 2008, p. 9)

Ewe Age	Age at lamb death	% Single	% Twin	% Triplet
Hogget	Born dead	1.9	5.6	-
	Birth to weaning	5.6	10.7	-
2-tooth Ewe	Born dead	4.8	4.2	9.5
	Birth to weaning	4.9	7.6	15.0
MA Ewe	Born dead	4.8	4.2	9.5
	Birth to weaning	4.9	7.6	15.0

4.3.10 Liveweight Profiles

In the model, weekly liveweight formed the basis for calculating the feed requirements for each animal class. In this research, all liveweights were reported as non-pregnant weight i.e. during pregnancy, ewe liveweight excludes the weight of the conceptus. This was done to avoid double counting the additional energy requirements during pregnancy (Hutchings, 1997).

For breeding females, replacement ewe lambs, and sire rams, liveweight was calculated as a function of mature ewe liveweight. In comparison, the liveweight of sale lambs was calculated as a function of daily growth rate and target carcass weight. Weekly liveweights of individual animals are shown in Appendix C.

MA Ewes

In the base model, mature ewe liveweight was assumed at 65kg in reference to the liveweight of a NZ Romney ewe (Meadows, 2008, p. 43). The liveweight of a Romney ewe was used as this is the most common breed of sheep in New Zealand (Beef + Lamb New Zealand Economic Service, 2015a).

In the model, liveweight throughout the season was kept relatively constant. This is justified due to the imbalance in energy costs associated with mobilising body reserves (Geenty, 1997, p. 25; Trafford & Trafford, 2011). However, due to intake restrictions and high energy demands associated with multiple litters, twin and triplet bearing ewes often lose weight in late pregnancy and early lactation. To account for this, twin and triplet bearing ewes were assumed to lose a total of 3 kg and 5 kg respectively over late pregnancy and early lactation. The weekly change in liveweight loss was based on the assumption that liveweight loss increased until two weeks after lambing. From two weeks after lambing, ewes have higher feed intakes (Litherland et al., 2007, p. 1), and as a result, it was assumed that liveweight loss reduced from this date. It was assumed that twin and triplet bearing ewes started regaining weight again from six weeks after lambing with the rate of liveweight gain being such that, by mating the following year, all liveweight that was lost during pregnancy and lactation would be regained. Ewes with single lambs were assumed to remain at constant liveweight throughout the year.

2-tooth ewes

For 2-tooth ewes, mating weight was assumed to be 90% of their mature body weight. In the base model, liveweight gain from mating to six weeks pre lambing was 23 g/day. The rate of liveweight loss in late pregnancy and early lactation was assumed to be the same as MA ewes. From six weeks post lambing to MA ewe mating, liveweight gain was 23 g/day for single, 40 g/day for twinning ewes and 52 g/day for triplet bearing ewes.

Hoggets

The model was set up so that hogget liveweight was dependent on whether that hogget was mated. This recognised the fact that a common justification for not mating hoggets is due to the difficulty of getting them up to target weights in time for mating due to a lack of feed (Kenyon, 2012, p. 10).

For mated hoggets, it was assumed that they reached 65% of mature ewe liveweight at mating. For a 65 kg ewe, this is 42 kg which is the minimum mating weight recommended by Kenyon (2012, p. 9). In the base model, this means that mated hoggets were required to grow at a rate of 109 g/day just prior to hogget mating. Unmated hoggets were not required to reach these target mating weights and were assumed to grow at a constant growth rate of 53 g/day.

While all hoggets were assumed to grow so that they reached 90% of mature ewe liveweight by 2-tooth mating, single bearing hoggets were assumed to remain at static liveweight over late pregnancy and early lactation while twin bearing hoggets were assumed to lose a total of 1.0 kg over this period. Hoggets that were mated but were “dry” were assumed to have a constant or linear liveweight gain from scanning to 2-tooth mating.

Ewe Lambs Replacements

From birth to weaning, the growth rate of single and twin replacement ewe lambs was the same as sale lambs. From weaning, the growth rate of twin lambs was such that their liveweight at hogget mating was 65% of mature weight. To ensure all hoggets were the same liveweight at mating date, irrespective of birth rank, it was assumed that the growth rate of single lambs was such that by the end of week 52 of the model, they had the same liveweight as twin lambs.

Sale Lambs

In the model, the liveweight of sale lambs in each week was a function of birth weight, growth rate, target carcass weight and dressing-out percentage.

a. Birth Weight

Birth weights were from the assumptions used by Cruickshank, Thomson and Muir (2008). These birth weights are consistent with those recommended for optimal survival (Dalton et al., 1980) and are shown in Table 4.4.

Table 4.4 Birth weight (kg) for lambs of different birth rank, sex and dam age

	Single		Twin		Triplet	
	Ewe	Ram	Ewe	Ram	Ewe	Ram
Hogget Dam	4.3	4.7	3.5	3.7	-	-
2-tooth Dam	5.3	5.7	4.3	4.5	3.8	4.0
MA Dam	5.3	5.7	4.3	4.5	3.8	4.0

b. Growth Rates

To account for the fact that lamb growth is highest during lactation and slows as lambs reach maturity (Fitzhugh, 1976; Kerr, 2010; Owens et al., 1993; Purchas et al., 1999), in the model, assumptions for lamb growth rate were made in reference to the period from lambing to weaning and then from weaning to sale. This distinction between pre-weaning and post-weaning lamb growth rate is common (Bray, Moss, Burton, & Saville, 1990; Litherland et al., 2007, p. 5; Shadbolt, 1982, p. 35).

At the level of the flock, the achieved pre-weaning and post-weaning lamb growth rates were a function of the birth parity proportions (single, twin, triplets), the ages of the ewes (hogget, 2-tooth and mature age), and the lamb gender ratio (assumed throughout as 1:1 ratio) (Loureiro et al., 2011; Thomson et al., 2004). Accordingly, and to avoid confusion arising from parameter interactions, in the model, input parameters for pre-weaning and post-weaning lamb growth relate to the pre-weaning or post-weaning growth rate of single lambs of mixed gender from mature-age ewes. In the baseline model this was set at 300 g/day during the pre-weaning period and 200 g/day in the post-weaning period. This is comparable to average growth rates of lambs in New Zealand (Table 4.7). Other categories of lambs grew at fixed proportions in relation to these single lambs from mature age ewes. For example, in the base model, twin and triplet lambs grew respectively at 0.86 and 0.75 the rate of singles during pre-weaning, while lambs from 2-tooth ewes and hoggets grew at 0.93 and 0.86 the rate of lambs from mature aged ewes. This meant that for any specific situation, there was an input parameter for the pre-weaning and post-weaning growth rate of single lambs from mature age ewes, and there was an achieved flock growth rate which depended not only on these parameters but on other flock parameters relating to flock structure and lambing performance.

Baseline pre-weaning and post-weaning growth rates for lambs of different sex, birth rank and dam age are shown in

<table>
<tr><td rowspan="2">Dam Age</td><td colspan="4">Single</td><td colspan="2">Twin</td><td colspan="2">Triplet</td></tr>
<tr><td colspan="2">Ewe Lamb</td><td colspan="2">Ram Lamb</td><td>Ewe Lamb</td><td>Ram Lamb</td><td>Ewe Lamb</td><td>Ram Lamb</td></tr>
<tr><td colspan="9">Pre-Weaning</td></tr>
<tr><td>Hogget Dam</td><td colspan="2">242</td><td colspan="2">274</td><td>208</td><td>235</td><td>-</td><td>-</td></tr>
<tr><td>2-tooth Dam</td><td colspan="2">242</td><td colspan="2">296</td><td>225</td><td>255</td><td>196</td><td>221</td></tr>
<tr><td>MA Ewe Dam</td><td>282</td><td colspan="2">300*</td><td>318</td><td>242</td><td>274</td><td>211</td><td>238</td></tr>
<tr><td colspan="9">Post-Weaning</td></tr>
<tr><td>Hogget Dam</td><td colspan="2">178</td><td colspan="2">202</td><td>166</td><td>187</td><td>-</td><td>-</td></tr>
<tr><td>2-tooth Dam</td><td colspan="2">178</td><td colspan="2">202</td><td>166</td><td>187</td><td>158</td><td>178</td></tr>
<tr><td>MA Ewe Dam</td><td>188</td><td colspan="2">200*</td><td>212</td><td>100</td><td>100</td><td>166</td><td>187</td></tr>
</table>

Table 4.5.

Table 4.5 Input parameters for lamb growth rate (*) and baseline pre-weaning and post-weaning lamb growth rates (g/day) for lambs of different birth rank, sex, and dam age

Conversion factors that were used to calculate the growth rate of lambs of different sex, birth rank and dam age were based on the average relationships reported in the literature (Table 4.6; Table 4.7; Table 4.8). An exception is that, in the model, it was assumed that the post-weaning growth rate of lambs born to hoggets was the same as the growth rate of lambs born 2-tooth ewes. This is in contrast to Cruickshank et al. (2008) and Loureiro et al. (2011) who report higher growth rates in

Table 4.6 The effect of sex on lamb growth rate

Author	Liveweight gain (kg) or growth rate (kg/day)		Conversion Factors	
	Ewe Lambs	Ram Lambs	Pre-weaning Ewe->Ram	Post-weaning Ewe->Ram
(Argue 1980, cited in Shadbolt, 1982)	0.266	0.318	1.20	
(Cruickshank et al., 2008)	0.239	0.260	1.09	
(Cruickshank et al., 2008)	0.100	0.105		1.05
(Everitt & Jury, 1966)	18.3	20.3		1.11
(Ferrell, Crouse, Field, & Chant, 1979)	0.200	0.250		1.25
(J. Hickford, personal communication, September 18, 2014)	0.25	0.28	1.12	
(Kerr, 2010, p. 66)			1.10 - 1.20	
(Mccoard, Koolaard, Charteris, & Luo, 2010)	15.85	16.95	1.07	
(Morris, McCutcheon, Parker, & Blair, 1994)	0.217	0.250	1.15	
(Thomson et al., 2004)	30.6	33.2	1.08	
Average			1.13	1.14

hogget lambs in comparison to lambs born to older dams. However, this is due to a compensatory growth effect (Oldham, Kirton, & Bass, 1999) as a consequence of low average growth rates in these studies and due to priority feeding of lambs born to hoggets.

Table 4.7 The effect of birth rank on pre-weaning and post-weaning lamb growth rate

Author	liveweight gain (kg) or growth rate (kg/day)			Conversion Factors	
	Single	Twin	Triplet	Single-> Twin	Twin-> Triplet
PRE-WEANING					
(Argue, 1980, cited in Shadbolt, 1982, p 39)	0.373	0.286	0.218	0.77	0.76
(Bray et al., 1990)	14.1	11.9		0.84	
(Bray et al., 1990)	14.1	12.0		0.85	
(Bray et al., 1990)	16.6	15.5		0.93	
(Bywater, Logan, Edwards, & Sedcole, 2011)	0.342	0.300	0.254	0.88	0.85
(Cruickshank et al., 2008)	0.273	0.247	0.223	0.90	0.90
(Geenty, 1997)	0.317	0.264		0.83	
(Kenyon et al., 2005)		22.8	19.0		0.83
(Kenyon et al., 2005)		20.6	18.0		0.87
(Litherland & Lambert, 2000)	0.273	0.220		0.81	
(Litherland, Lambert, & McLaren, 1999)	0.280	0.240		0.86	
(Loureiro et al., 2011)	0.266	0.219		0.82	
(Morris, McCutcheon, et al., 1994)	0.250	0.217		0.87	
(Muir, Smith, & Lane, 2003)	0.437	0.407	0.380	0.93	0.93
(Muir et al., 2000)	0.343	0.292		0.85	
(Parker & McCutcheon, 1992)	0.268	0.221		0.82	
(Peterson, Kenyon, & Morris, 2006)		17.0	14.9		0.88
(Thomson et al., 2004)	0.334	0.295	0.273	0.88	0.93
Average				0.86	0.87
POST-WEANING					
(Bywater et al., 2011)	0.163	0.128		0.79	
(Cruickshank et al., 2008)	0.114	0.096	0.091	0.84	0.95
(J. Hickford, personal communication, September 18, 2014)	0.048	0.05	0.049	1.04	0.98
(Loureiro et al., 2011)	0.047	0.055		1.09	
(Mccoard et al., 2010)	17.25	15.55		0.90	
Average				0.93	0.96

Table 4.8 The effect of dam age on pre-weaning and post-weaning lamb growth rate

Author	liveweight gain (kg) or growth rate (kg/day)			Conversion Factors	
	MA Ewe	2-tooth Ewe	Hogget	MA Ewe-> 2-tooth Ewe	MA Ewe-> Hogget
PRE- WEANING					
(Cruickshank et al., 2008)	0.263	0.247	0.238	0.94	0.90
(Kerr, 2010, p. 30)	25.0		21.0		0.84
(Loureiro et al., 2011)	0.260		0.223		0.86
(Notter, Borg, & Kuehn, 2005)	21.5	20.0	18.0	0.93	0.84
Average				0.93	0.86
POST- WEANING					
(Cruickshank et al., 2008)	0.101	0.096	0.110	0.95	1.09
(Loureiro et al., 2011)	0.051		0.051		1.00
Average				0.95	1.04

Although post-weaning growth rate can be assumed to be linear without significant error, growth rate during the pre-weaning period shows considerable variation and is linked with the ewe lactation curve (Geenty, 1979; Litherland et al., 2007, p. 5). As a consequence, in this research, pre-weaning growth rate was adjusted to account for changes in growth rate associated with the stage of lactation. Modifiers used to adjust weekly growth rate are shown in Table 4.9 and result in a similar growth curve to that used in FARMAX (Litherland et al., 2007, p. 5). In the model, separate modifiers were used to adjust the growth rate of lambs born to hoggets. This is a consequence of the shorter length of lactation.

Table 4.9 Growth rate modifiers during the lactation period

Week	Ewes (12 week lactation)	Hoggets (10 week lactation)
1	1.04	1.00
2	1.09	1.05
3	1.13	1.08
4	1.14	1.09
5	1.12	1.07
6	1.09	1.04
7	1.04	1.00
8	0.99	0.95
9	0.93	0.89
10	0.87	0.83
11	0.81	
12	0.75	

For simplification, in the calculation of lamb growth rates, it was assumed that lamb deaths in twin and triplet litters had no effect on the growth rate of surviving lambs. It was also assumed that the process of weaning lambs did not result in a "weaning check" in the days immediately following weaning. Rather, all lamb were assumed to grow at a linear rate for the duration of the post-weaning period.

c. Target Carcass Weight

In the base model, target carcass weight was 18 kg as this has been the approximate industry average slaughter weight since 2012 (Beef + Lamb New Zealand Economic Service, 2016, p. 15).

Sire Rams

For sire rams, it was assumed that liveweight remained constant throughout the year and was assumed to be 25% greater than mature ewe liveweight. This is similar to the difference in liveweight between ewes and rams recorded by Meadows (2008). In the base model, given that ewe liveweight was 65kg, the liveweight of sire rams was therefore 81 kg.

4.3.11 Energy Requirements

In the model, individual energy requirements were calculated daily in MJME and then summed to give the total energy demands for each week. The equations used to calculate individual energy requirements were based on the generalised equations adopted by the Australian Standing Committee on Agriculture (Freer et al., 2007; SCA, 1990). Total energy requirements were calculated using the factorial approach with total energy requirement being the sum of the MJME required for maintenance, liveweight gain (or loss), pregnancy, and the ewe and lamb lactation requirement. For simplification, increases in energy requirement as a result of shearing (Trafford & Trafford, 2011, p. A8) was ignored. For the baseline model, total weekly energy requirements for each animal are summarised in Appendix D.

Feed Quality

Being demand-driven, this research was modelled at that livestock sub-level of the farm system. Therefore this research intentionally does not account for plant-animal interactions. However, as energy requirements of sheep are dependent on the energy density of their feed (Freer et al., 2007; SCA, 1990), this research necessarily assumed underlying estimates of feed quality. For ewes, it was assumed that the energy content of their pasture was 10.5 MJME/kg DM during the periods of pregnancy and during the post-weaning period. During lactation, it was assumed that the energy content of their pasture was 11 MJME/kg DM. For lambs, it was assumed that they received priority feeding and therefore it was assumed that the energy content of their pasture was 11 MJME.

Unmated hoggets were assumed to be on feed of the same quality as ewes. However, mated hoggets were assumed to have priority feeding and were assumed to have a feed quality of 11 MJME during pregnancy, lactation and in the post-weaning period.

Maintenance Requirement

Maintenance energy requirement is the energy required to maintain homeothermy and vital processes in the body and in physical activities including those associated with feeding (Freer et al., 2007, p. 14). In the model, maintenance energy requirement was calculated as the sum of requirements for basal metabolism and those energy costs associated with grazing and walking:

$$\mathrm{ME_m} = \mathrm{ME_b} + \mathrm{ME_{graze}}$$

Where:

$\mathrm{ME_b}$ = Basal metabolism
$\mathrm{ME_{graze}}$ = ME associated with grazing and walking

In calculating maintenance requirements, it was assumed that the ambient temperature was above the lower critical temperature for sheep. Therefore, it was assumed that no extra energy was required to maintain body temperature and consequently the term ME_{cold} in the generalised equations for maintenance requirement (Freer et al., 2007, p. 19) was omitted. Also, although additional energy was required to maintain the productive tissues, following Nicol and Brookes (2007), these 'support' costs were attributed to production rather than to maintenance. This approach was used so that maintenance energy costs were not dependent on the level of production.

The ME requirement for basal metabolic rate is a function of liveweight, sex, age, and feed quality and was calculated using the equation:

$$\mathrm{ME_b} = \mathrm{Sex} \times \frac{0.28\mathrm{Lwt}^{0.75} \times \exp(-0.03\mathrm{Age})}{\mathrm{k_m}}$$

Where:

Sex = 1.0 for ewes and 1.15 for rams
Lwt = Liveweight (kg), excluding conceptus
Age = 1 for lambs and hoggets, 2 for 2-tooth ewes and 4 for MA ewes
$\mathrm{k_m}$ = Net efficiency of use of ME for maintenance $= 0.02 \times M/D + 0.5$
M/D = ME concentration of feed dry matter (MJME/kg DM)

The energy costs associated with grazing included the energy required for eating (in addition to the energy requirements of housed animals) and the energy required for the walking and was calculated with the equation:

$$\mathrm{ME_{graze}} = \left[\left(0.02 \times \mathrm{DMI}\ (0.9 - \mathrm{D})\right) + \left(0.0026 \times \mathrm{T} \times \frac{(\mathrm{TSR/SD})}{(0.057 \times \mathrm{PM} + 0.16)}\right) + (0.0026 \times \mathrm{Hkm}) + (0.028 \times \mathrm{Vkm}) \right] \times \mathrm{Lwt}/\mathrm{k_m}$$

Where:

DMI = Dry matter intake
D = Dry matter digestability, calculated as $M/D/15.088$
T = Terrain, which ranges from 1.0 for flat land and 2.0 for steep land
$\mathrm{TSR/SD}$ = Relative stocking rate which takes the value of 1.0 for sheep
PM = Pasture mass (t DM/ha)
Hkm = Horizontal km walked
Vkm = Vertical km climbed
Lwt = Liveweight (kg), excluding conceptus
$\mathrm{k_m}$ = Net efficiency of use of ME for maintenance $= 0.02 \times M/D + 0.5$
M/D = ME concentration of feed dry matter (MJME/kg DM)

In the base model, as feed demands were not calculated in respect to a specified feed supply context, in calculating the energy costs for grazing, it was assumed that the class of land was medium hill country. The values for terrain, pasture mass and the vertical and horizontal distance walked for this land type were from Nicol and Brookes (2007, p. 170) and are shown in Table 4.10. In this research $\mathrm{ME_{graze}}$ was calculated assuming a constant dry matter intake of 1.0 kg DM/day for lambs and unmated hoggets, 1.5 kg DM/day for single bearing ewes, 1.8 kg DM/day for twin bearing ewes and 2.0 kg DM/day for triplet bearing ewes. In the calculation of $\mathrm{ME_{graze}}$, a constant DM intake was assumed in order to avoid circular referencing within the model. However, this simplifying assumption is consistent with this research being demand-driven and at the livestock sub-level of the farm system and is unlikely to result in any significant error in feed energy requirements.

Table 4.10 Assumed values for the calculation of $\mathrm{ME_{graze}}$

Terrain (medium hill country)	1.5
Horizontal km walked	1.0
Vertical km climbed	0.1
Pasture Mass (t DM/ha)	1.5

Liveweight Gain (loss)

For mature ewes, the energy required for liveweight gain was assumed to be 55 MJME/kg liveweight gain (Nicol & Brookes, 2007). For lambs, hoggets, and 2-tooth ewes, the ME required for liveweight gain ($\mathrm{ME_g}$) was calculated as a function of liveweight in relationship to mature body size using the equation:

$$\mathrm{ME_g} = 1.1 \times \mathrm{NE_g}/\mathrm{k_g}$$

Where:

$\mathrm{NE_g}$ = Net Energy of gain
$= (0.92 \times \mathrm{LWG}) \times ((6.7 + (((920 \times \mathrm{LWG}) / (4 \times (\mathrm{SRW}^\wedge 0.75))) - 1)) + (20.3 - (((6.7 + (((920 \times \mathrm{LWG}) / (4 \times (\mathrm{SRW}^\wedge 0.75))) - 1)) / (1 + \mathrm{EXP}(-6 \times ((\mathrm{Lwt} / \mathrm{SRW}) - 0.4))))$

LWG = Liveweight gain (kg/day)
SRW = Standard reference weight or mature body size (kg)
$\mathrm{k_g} = (\mathrm{M/D} \times 0.042) + 0.006$
M/D = ME concentration of the feed dry matter (MJME/kg DM)

Note that the ME requirement for liveweight gain, calculated as NE/k_g, was increased by 10% to account for the energy costs of supporting the actively growing muscle and fat cells (Nicol & Brookes, 2007). In the base model, the mature body size for ewe lambs was assumed to be equal to the mature size of MA ewes and the mature body size of ram lambs was assumed to be equal to the body weight of sire rams. The MJME substituted per kg liveweight loss was assumed to be 30 MJME (Nicol & Brookes, 2007) and was assumed to be constant irrespective of physiological state or age.

Pregnancy Requirement

Pregnancy requirements ($\mathrm{ME_p}$) were calculated as a function of the number of lambs per litter, birth weight, and time from conception using the equation:

$$\mathrm{ME_p} = \mathrm{n}\left(\frac{\mathrm{BirthWt}}{4}\right)\left(\left(\mathrm{EXP}\left(7.64 - 11.46 \times \mathrm{EXP}(-0.00643 \times \mathrm{Days})\right)\right) \times 0.074 \times \mathrm{EXP}(-0.00643 \times \mathrm{Days})\right) / \mathrm{k_p}$$

Where:

n = Number of lambs/litter
$\mathrm{BirthWt}$ = Birth weight of offspring (kg)
Days = Number of days since conception
$\mathrm{k_p}$ = Efficiency of pregnancy $= 0.133$

For simplification, pregnancy requirements were calculated using the average birth weight of ram and ewe lambs. This was done so that pregnancy requirements were independent of the sex of lambs.

Lactation Requirement (ewe and lamb)

In this research, the method used to estimate the energy requirements of lactating dams and their offspring was based on the approach used by Nicol and Brookes (2007, p. 170). In this approach, lactation requirements were estimated as a function of lamb liveweight gain and required an estimate of the proportion of total energy from milk and pasture. The lactation requirement was calculated using the following steps:

1. **Estimate the Net Energy requirement of each lamb**

   The Net Energy requirement (NE) of each lamb was calculated by adding the NE requirement for maintenance and growth. The NE required for lamb maintenance ($\mathrm{NE_m}$) was calculated using the equation:

$$\mathrm{NE_m} = \mathrm{Sex} \times 0.27\mathrm{Lwt}^{0.75} + NE_{graze}$$

Where:

$NE_{graze} = 0.021286 \times Lwt$
$\mathrm{Sex} = 1.0$ for ewe lambs and 1.15 for ram lambs
$\mathrm{Lwt} =$ Lamb liveweight (kg)

In this equation, the NE requirements for grazing was calculated assuming the terrain was medium hill country. The NE required for lamb growth ($\mathrm{NE_g}$) was calculated using the equation:

$$\begin{aligned}\mathrm{NE_g} = \ & (0.92 \times \mathrm{LWG}) \times ((6.7 + (((920 \times \mathrm{LWG}) \,/\, (4 \times (\mathrm{SRW}\text{^}0.75))) - 1)) \\ & + (20.3 - (((6.7 + (((920 \times \mathrm{LWG}) \,/\, (4 \times (\mathrm{SRW}\text{^}0.75))) - 1)) \\ & / \, (1 + \mathrm{EXP}(-6 \times ((\mathrm{Lwt} \,/\, \mathrm{SRW}) - 0.4))))\end{aligned}$$

Where:

$\mathrm{LWG} =$ Lamb growth rate (kg/day)
$\mathrm{Lwt} =$ Liveweight (kg)
$\mathrm{SRW} =$ Standard reference weight (kg). For ewe lambs this was the mature size (kg) of ewes. For ram lambs this was the mature size (kg) of the sire rams.

2. Estimate the NE from Milk and Pasture

The NE requirement from milk was calculated by multiplying the total NE requirement for each lamb by an estimate of the percentage of energy from milk. Assumptions for the percentage of energy from milk are shown in Table 4.11. These assumptions are consistent with data from Kerr (2010, p. 23). At birth, 100% of energy was assumed to come from milk. However, the increasing energy requirements of the lamb combined with reductions in milk yield in late lactation (Litherland et al., 2007) requires lambs to eat a growing amount of pasture to obtain the required energy needed from lamb growth and maintenance. Although ewes with twins and triplets have higher milk yields in comparison to ewes with single lambs (Geenty, 1979; Peart et al., 1975), because this is shared, the total energy requirement per lamb from milk is less. As a consequence, multiple born lambs are required to eat a greater proportion of pasture and must start eating pasture at an earlier age (Peterson et al., 2006).

Table 4.11 Assumptions for the percentage of energy from milk over the lactation period for single, twin and triplet lambs

Week of Lactation	Single	Twin	Triplet
1	100%	100%	100%
2	100%	100%	100%
3	100%	100%	91%
4	100%	91%	83%
5	92%	83%	74%
6	85%	74%	66%
7	77%	66%	57%
8	70%	57%	49%
9	62%	48%	40%
10	55%	40%	32%
11	47%	31%	23%
12	40%	23%	15%

3. Calculate the ME equivalent of Milk

The ME equivalent of the milk was calculated by dividing the NE requirement from milk by the efficiency for energy use. To do this it was assumed that milk energy was first used for maintenance and then for growth. Therefore, the NE requirement for gain from milk was calculated by subtracting the NE from milk by the NE requirement for maintenance. The ME required for maintenance was calculated using the equation $\mathrm{ME_m} = NE_m/k_m$, where k_m is the efficiency of energy use for maintenance for milk diets and was assumed to be 0.85

(Freer et al., 2007, p. 68). The ME required for growth from milk was calculated by using the equation $\mathrm{ME_g} = NE_g/k_g$, where k_g is the efficiency of use for growth from milk diets and was assumed to be 0.7 (Freer et al., 2007, p. 68). To account for the 10% extra maintenance energy costs required for production, the ME required from growth from milk was then multiplied by 1.1.

4. Calculate the ME requirement for Milk Production

The ME requirement for milk production was calculated by dividing the Gross Energy (GE) of milk by the efficiency of energy use for lactation. The GE of milk was calculated by dividing the ME equivalent of milk by the digestibility of milk. This was assumed to be 95% (Nicol & Brookes, 2007). The efficiency of energy used for lactation ($\mathrm{k_l}$) was calculated using the equation $\mathrm{k_l} = (0.02 \times \mathrm{M/D}) + 0.05$, where M/D is the ME concentration of the feed measured in MJME/kg DM.

5. Estimate the extra grazing cost for the ME intake by the ewe for milk

The grazing energy cost for the extra ME intake by the ewe for milk was calculated using the equation:

$$ME_{graze} = \left(0.02 \times \mathrm{DMI}\ (0.9 - \mathrm{D})\right) \times Lwt/k_m$$

Where:

DMI = Extra dry matter intake of the ewe for milk = MJME for milk production divided by the ME concentration of feed dry matter (MJME/kg DM)
D = Dry matter digestability, calculated as $M/D/15.088$
Lwt = Liveweight (kg), excluding conceptus
k_m = Net efficiency of use of ME for maintenance $= 0.02 \times M/D + 0.5$
M/D = ME concentration of feed dry matter (MJME/kg DM)

Adding the ME for milk production and the extra energy cost for grazing gives the total MJME requirement for milk.

6. Calculate the ME requirement for lamb maintenance and lamb growth from pasture

First, the total NE requirement from pasture used for maintenance and growth was calculated by subtracting the total NE required by each lamb for maintenance and growth by the NE supplied by milk for maintenance and growth.

Next, the ME requirement for lamb *maintenance* from pasture was then calculated by dividing the NE for lamb maintenance from pasture by the efficiency of energy use for maintenance (k_m) for grass diets using the equation $\mathrm{ME_m} = NE_m/k_m$, where $k_m = 0.02 \times M/D + 0.5$ and M/D is the ME concentration of the feed dry matter measured in MJME/kg DM.

The ME requirement for *growth* from pasture was then calculated by dividing the NE for growth by the efficiency of energy use for growth for grass diets (k_g) using the equation $\mathrm{ME_g} = 1.1 \times NE_g/k_g$, where $\mathrm{k_g} = (\mathrm{M/D} \times 0.042) + 0.006$, and M/D is the ME concentration of the feed dry matter measured in MJME/kg DM. Note that the NE requirement for lamb growth is multiplied by 1.1 to account for the 10% extra maintenance energy costs required for production.

7. Calculate the grazing cost of the lamb for the ME intake from pasture

The grazing energy cost of the lamb for the ME intake from pasture was calculated using the equation:

$$ME_{graze} = \left(0.02 \times \mathrm{DMI}\ (0.9 - \mathrm{D})\right) \times Lwt/k_m$$

Where:

DMI = Dry matter intake from pasture = MJME for maintenance and growth from pasture divided by the ME concentration of feed dry matter (MJME/kg DM)
D = Dry matter digestability, calculated as $M/D/15.088$
Lwt = Liveweight (kg) of the lamb
k_m = Net efficiency of use of ME for maintenance = $0.02 \times M/D + 0.5$
M/D = ME concentration of feed dry matter (MJME/kg DM)

8. Total MJME for lactation

The total MJME for lactation was calculated by adding the MJME requirement for milk production, the MJME requirement from pasture for lamb maintenance and growth and the extra energy cost for grazing.

An important implicit assumption in using the approach described above to calculate the lactation energy requirement is that increases in pre-weaning growth rate are achieved by an increase in the milk production of the ewe. This assumption is consistent with the findings of Peart (1967) and Geenty, Clarke, and Wright (1985) who observe a strong positive correlation between milk production and the growth rate of lambs. In essence, it reverse engineers the relationship as used in other models such as that of Cruickshank et al. (2009), where pre-weaning lamb growth rate was calculated as a function of milk yield. The need for reverse engineering is a direct consequence of the model being demand-driven.

Although energy requirements for lactation form part of the total feed demands of ewes, in the linear programming model, lactation requirements were allocated to the progeny. This method was also used by Woodford (1997, p. 165) and was done for convenience and to avoid the allocation of lactation requirements to non-lactating females.

4.4 Summary

In this chapter, the biological model that was developed to investigate the relationships between key parameters of the sheep livestock system to both feed conversion efficiency and the seasonality of feed demand has been presented. This model was constructed in Microsoft Excel^{TM}. First, individual animal energy requirements were simulated in relation to assumptions from previous research. Linear programming was then used to bring these outputs together within a whole-of-system framework. The unique characteristic of the model is that it was demand-driven. Although the overall supply of energy was constrained exogenously as a model input, the allocation of feed between periods of the year was determined endogenously within the model. For example, in response to changes in specified animal performance levels and individual animal energy requirements, feed supply activities supply feed to individual periods from the common annual pool of exogenous feed, which, in this research, was set at a fixed but arbitrary limit of 10 million MJME. Key outputs of the model included flock structure, numbers of animals in each age class and birth rank category, and total system feed demand, meat production and feed conversion efficiency (calculated as the g meat carcass per MJME of feed demand). In the baseline model, the sheep livestock system represents a steady-state self-contained breeding-finishing system and was based on industry average animal performance levels.

Although the linear programming model developed in this study was too large to include as an appendix to this thesis, the full model is available to researchers and can be obtained from the author or from the supervisors of this thesis.

In the next chapter, the baseline results of the linear programming model are presented.

Chapter 5

Base Model Results, Verification and Validation

5.1 Introduction

In the preceding chapter, the methods and assumptions used to construct the baseline linear programming model were shown. A summary of baseline values for key livestock system parameters are shown in Table 5.1. In this chapter, the outputs of the baseline linear programming model are presented. This is then followed by a discussion of some issues regarding model verification and validation in relation to these baseline results.

Table 5.1 Baseline values for key livestock production parameters

Parameter	Baseline Value
Ewe lambing percentage (lambs tailed per ewe mated)	120%
Ewe size	65 kg
Pre-weaning liveweight gain*	300 g/day
Post-weaning liveweight gain*	200 g/day
Hogget lambing percentage (lambs tailed per total hogget at mating)	30%
Lamb carcass weight	18 kg
Cull age (years)	7.3 years
Ewe mortality rate	3%

* Growth rates relate to a single lamb of mixed sex born to a MA ewe. Whole-of-flock average lamb growth rates were derived from this input parameter together with flock structure and relative growth rate assumptions of each lamb category.

5.2 Base Model Results

In the base model, a total of 31,301 kg of meat carcass was produced giving a feed conversion efficiency of 3.13 g carcass/MJME. Of total meat carcass production, 78% was lamb carcass and 22% was mutton carcass. In total, 29% of annual feed demand was required during ewe pregnancy (week 1 to week 21), 33% was required during ewe lactation (week 22 to week 33) and 38% was required post-weaning (week 34 to week 52).

At ewe mating date, there were a total of 1,313 ewes (1,043 MA ewes and 270 2-tooth ewes), 272 hoggets, and 19 sire rams. Of lambs born, 1,352 lambs were sold and 272 ewe lambs were kept as replacements.

Whole-of-system weekly feed demand of the baseline livestock system are shown in Figure 5.1. At the start of week one (ewe mating date), breeding ewes (2-tooth and older), hoggets, sale lambs and sire rams accounted for 78.4%, 19.1%, 1.1% and 1.4% of total feed demand respectively. From mating date, total energy demand of the sheep system decreased slightly as the last of the lambs from the previous season were sold. Minimum weekly feed demand occurred in week five and was 1.2% of annual feed demand. From this point feed demand increased due to the increasing pregnancy requirement of pregnant females. At the start of week twelve of pregnancy there was a slight reduction in total system feed demand as a consequence of dry ewes being culled after scanning. From scanning, feed demand started to increase rapidly due to the feed requirements of pregnancy increasing at an exponential rate.

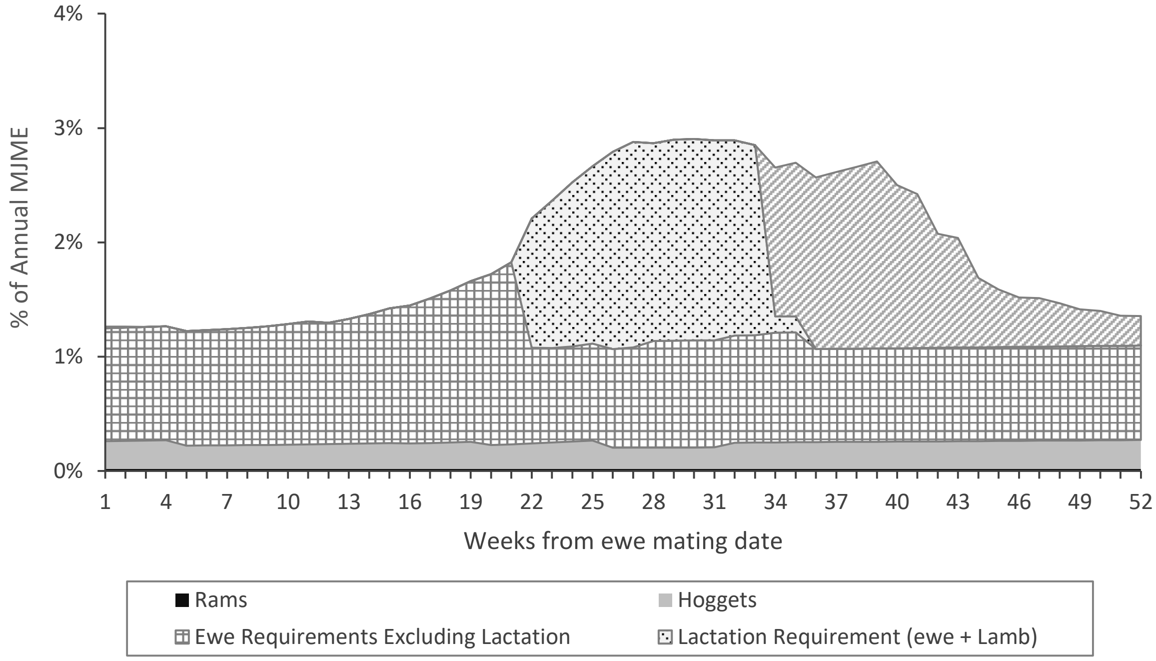


Figure 5.1 Weekly feed demand of the sheep livestock system, measured as the percentage of annual total MJME, starting from ewe mating date and categorized by stock class

Ewe lambing occurred at the start of week 22 and caused a step increase in total system feed demand as a result of the significant energy costs associated with lactation. In week 22, the lactation energy requirement (ewe lactation plus lamb requirements) accounted for 51.2% of total energy requirement and the energy requirement of ewes (excluding lactation requirement) accounted for 37.9% of total feed demand. The energy requirement of hoggets accounted for 10.1% of total feed demand and the energy demand of sire rams remained low at 0.8% of total feed demand. From lambing date, total system feed demand increased in the early part of the lactation period. This was due to increasing milk production, lamb growth rates and increasing maintenance requirements of the growing lambs. However, due to lamb deaths being assumed to occur at this time, there was a small reduction in total feed requirement six weeks after lambing. Also, as the lactation period progressed, ewe milk production and lamb growth rates declined. This resulted in a small decrease in total system energy requirement in the last few weeks of the lactation period. This was despite reductions in lactation requirement in late lactation being partly offset by an increase in the energy demand of ewes due to twin and triplet bearing ewes regaining the weight lost during late pregnancy and early lactation. Maximum weekly feed demand occurred in week 30 and was 2.9% of annual feed demand.

For ewes, weaning occurred at the start of week 34 (12 weeks after lambing date). This meant that energy was no longer required for milk production which caused another step change in the total feed demands of the sheep livestock system. Two weeks after ewe weaning date, feed demands of the sheep livestock system reduced again due to ewe mortality and ewe culling. System feed demand also reduced as lambs born to hoggets were weaned at this time.

From week 36, the total system feed demand began to increase again as a result of increasing feed requirements of growing lambs. However, as individual lamb classes reached target slaughter weight, total feed demand of the livestock system eventually reduced. In week 52, the feed demand of ewes accounted for 61% of total feed demand and the feed demand of hoggets, lambs and rams accounted for 18.7%, 18.9% and 1.3% of total feed demand. At the end of week 52, replacement ewe lambs aged up to hoggets, hoggets aged up to 2-tooth ewes, and 2-tooth ewes aged up to MA ewes.

5.3 Verification

Model verification and validation are key steps in the modelling process (Albright, Winston, & Zappe, 2006, p. 25). Model verification, also called internal model validation, is the process of checking that the model is logically and mathematically correct and that the data used is correct (Anderson et al., 2013, p. 745; Daellenbach & McNickle, 2005, p. 120). It involves checking that the mathematical expressions correctly represent the assumed relationships and that they have been correctly implemented in the computer program. Model verification is therefore largely a process of error-prevention and de-bugging (Daellenbach & McNickle, 2005, p. 120) and is performed concurrently during the model synthesis and construction phase.

In this research, the following verification steps and techniques were used:

- Comparison with hand calculations: Computer results for a limited number of intermediate calculations were compared with hand calculations.
- Reasonable results: Tests were performed to verify that the outputs from the model seemed reasonable.

- Checks for dimensional consistency: Checks were made to verify that the units in the right hand side of an equation were the same as the units in the left hand side.

- Unique input cells: In the spreadsheets, equation constants were provided as input into unique cells, referenced by all formulas that used them, rather than being inserted as numbers separately into each formula. "This ensures that any changes will automatically be carried forward to all formulas where that constant is used" (Daellenbach & McNickle, 2005, p. 120).

- Progressive model development: As succinctly stated by Mencarini (2013, p. 14), "the model was developed sequentially, starting with the simplest version before adding the next level of complexity".

- Backup files: To help identify the circumstances in which an error may have occurred, a folder was kept with files containing all the previous versions of the model.

- Master copy: To avoid mistakes, changes to the model were always made to the master copy of the model.

- Model documentation: Records of errors, changes and suggestions on how to improve the model were kept. This helped clarify the specific conditions and assumptions associated with each updated version of the model.

5.4 Validation

Externally validating a computer model involves determining whether the model provides a sufficiently accurate representation of reality to allow for insight and useful answers (Albright et al., 2006, p. 25; Anderson et al., 2013, p. 745; Daellenbach & McNickle, 2005, p. 121). As this question is dependent on the purpose for building the model and the intended use of its solution, model validation is largely a process of judgment and is therefore subjective (Daellenbach & McNickle, 2005, p. 121). As such, and consistent with a relativist/holistic philosophy of science, it is not possible to prove that a model is valid in an absolute sense (Barlas & Carpenter, 1990; Robinson, 1997). Hence, model validation is a question of establishing the credibility of the model in relation to purpose.

While model validation is presented here sequentially following presentation of the baseline model results, practically, model validation has been performed concurrently during the model synthesis and construction phase. As explained by Dent and Blackie (1979), model validation is an ongoing process during which confidence in the model steadily increases through a succession of formal and informal tests. Up to that point, model validity has remained only probable by the appropriateness of its underlying assumptions (Reichenbach, 1951).

In this research, the external validity of the baseline model was assessed through comparison of the results to other models, sensitivity analysis and examination for sensible results.

5.4.1 Comparison Against Known Results

It was found that at 3.1 g carcass per MJME, baseline feed conversion efficiency was broadly comparable to that reported by other studies. For example, assuming a conversion factor of 10.5 MJME/kg DM, Brookes, Lowe, and Garrick (1998) reported a feed conversion efficiency of 3.5 g carcass/MJME. Also, although Cruickshank et al. (2009) measure methane efficiency (kg CH_4/lamb sold), by extrapolation, their results indicate that feed conversion efficiency of the sheep flock can be approximated as 2.5 g carcass/MJME[6]. The feed conversion efficiency reported in this research is also roughly comparable to alternative livestock species. For example, Woodford (1997) calculated that a steady-state deer herd will produce 2.6 g venison carcass per MJME. These results also compare to Fennessy and Thompson (1989) who calculated the feed conversion efficiency of a deer herd and, depending on a number of production parameters, reported efficiencies between 2.22 and 3.79 g venison carcass/MJME.

5.4.2 Sensitivity Analysis

Sensitivity analysis involves examining the sensitivity of the model to changes in model parameters for the presence of a logical explanation. The process of sensitivity analysis may also direct the modeller back to problem formulation and model construction if, for example, it reveals shortcomings in a particular part of the model (Dent & Blackie, 1979). Considering the purpose of this chapter was to present the baseline model, sensitivity analysis in this chapter is restricted to testing the sensitivity of *equation* parameters. The sensitivity of *production* parameters are shown in the following chapters. The key equation parameters that are tested are the energy requirements for maintenance and growth as expressed in equation coefficients.

All of the equations relating to feed energy demand are deterministic and have been published that way in prior research (Freer et al., 2007; SCA, 1990). Accordingly, the precision of the baseline results will reflect the inherent precision of these equations. To establish confidence in the model, the

[6] Of total methane output of 15,814.11 kgCH_4, 6,945.08 kgCH_4 can be apportioned to the 1000 ewes and 8,869.03 kgCH_4 can be apportioned to the 1277 lambs. With methane output calculated as 2.09 gCH_4/Kg DM for ewes and 16.8 gCH_4/kg DM for lambs, this results in a total requirement of 860,218.93 kg DM or, with feed quality averaging 10.425MJME/kg DM, 8,967,782 MJME. Thus, with 989 lambs slaughtered at an average carcass weight of 17.4 kg and with an additional assumption that 22% of total carcass output being from cull ewes, the carcass sold is 22,062.3 kg giving a feed conversion efficiency of 2.46 g carcass/MJME.

sensitivity of the base model result was tested for a 10% change in the coefficients for maintenance energy, energy for liveweight gain/loss ("growth" energy), lactation energy and pregnancy energy (Table 5.2). The importance or otherwise of these issues is left to subsequent chapters where the specific research questions are addressed.

Table 5.2 Sensitivity of whole-of-system feed conversion efficiency (g carcass/MJME) to ± 10% change in the MJME input energy requirement for maintenance, growth, pregnancy and lactation

	+10% MJME	Base	-10% MJME	Change in FCE from Base to: +10%	-10%
ME maintenance (lambs- post weaning)	3.10	3.13	3.16	-0.84%	0.85%
ME growth (lambs- post weaning)	3.10	3.13	3.16	-0.87%	0.88%
ME maintenance (ewes, hoggets & sire rams)	2.97	3.13	3.31	-5.51%	5.83%
ME growth (ewes, hoggets & sire rams)	3.12	3.13	3.14	-0.40%	0.40%
ME pregnancy (ewes & hoggets)	3.12	3.13	3.14	-0.42%	0.42%
ME lactation (ewe & lamb requirement)	3.07	3.13	3.19	-1.79%	1.83%

5.4.3 Sensible Results

To a large extent, the results presented in this research have been validated "in-action" by examination of model outputs to determine if they are sensible, expected, and explainable. As noted by Albright et al. (2006, p. 25), "if model outputs behave as expected then this is another piece of evidence that the model is reasonable". The model was therefore validated by the fact that the outputs of the model seemed sensible and that these results could be explained.

5.5 Summary

In this research, the feed conversion efficiency of the baseline model of the sheep livestock system was calculated as 3.13 g carcass/MJME and the whole-of-system feed demand during the pregnancy, lactation and post-weaning periods was 29%, 33% and 38% respectively. To increase the confidence in the model, verification and validation steps have been undertaken. In relation to the base model, key validation steps included comparison of model outputs to known results, sensitivity analysis, and examination of model outputs for sensible results. However, as validation relates to purpose, the issue of validation will be revisited in subsequent chapters in relation to the specific issues explored in those chapters.

In the next chapter, the effect of livestock production parameters on feed conversion efficiency and feed demand seasonality are tested one-at-a-time in relation to the baseline model as reported in this chapter.

Chapter 6

Single Factor Experiments

6.1 Introduction

To test the impact of key livestock parameters on both feed conversion efficiency and feed demand seasonality, post-optimality experimentation of the initial baseline linear programming model was carried out using the technique known as parametric programming (Hazell and Norton pg. 125). This is a method for the systematic consideration of the impact of a sequence of incremental changes in any of the linear programming model coefficients. First, key parameters of the livestock system were varied between feasible limits. After each change, individual feed requirements were simulated within Microsoft Excel™ and the coefficients to the linear programming model calculated. The linear programming model was then re-run to calculate changes to overall stock numbers, whole-of-system weekly feed demands, meat output and feed conversion efficiency (g carcass/MJME). By testing a range of values for each livestock parameter, relationships to both feed conversion efficiency and the seasonality of feed demand were then determined.

While there are other approaches to parametric programming (Hazell & Norton, 1986, p. 126), in this research, a fixed interval approach was used. This means that changes to livestock parameters were based on a fixed interval of change. This interval varied depending on the livestock parameter being tested. However, for most parameters, five to seven values were tested for each livestock parameter with the lower and upper limits of each parameter value being based on common limits and within known biological feasibility. Also, where possible, the baseline value for each parameter was half way between the minimum and maximum values tested. However, as baseline values were chosen to represent industry averages (which, for some parameters, were much closer to lower limits), this was not always possible.

Generally, parameters within a model should be first tested one-at-a-time in relation to the baseline scenario and then be tested in-combination through the simultaneous change in multiple parameters. The purpose of this chapter is to present the results of single factor experimentation of key livestock parameters which involves testing input parameters under a *ceteris paribus* condition, whereby the effect of a change in a single parameter is considered with all other livestock parameters held constant. The combined effect of simultaneous changes in different livestock parameters is explored in Chapter 7.

In this research, key parameters tested include ewe lambing percentage (lambs tailed per ewe mated), pre-weaning and post-weaning lamb liveweight gain, ewe size, target carcass weight, hogget lambing (hogget lambs tailed per total hogget), age of ewe culling, and ewe mortality rate. Although there a many more production parameters of the sheep livestock system, the choice to of included parameters was judgemental, and this choice was made in discussion between the author and the supervisors of this thesis.

Following the results of single-factor experimentation, a discussion on the effect of livestock parameters on both feed conversion efficiency and the seasonality of feed demand is presented. The sensitivity of other livestock parameters is also discussed. The chapter concludes with a summary of key research findings.

6.2 Ewe Lambing Percentage

To test the effect of reproductive performance, the prolificacy rate or average litter size of ewes (lambs born per ewe lambing) was adjusted so that the average whole-of-flock lambing percentage (lambs tailed per ewe mated) of 2-tooth and MA ewes ranged from 110% to 170%. Given the baseline assumptions for ewe dry rate, lamb survival, birth rank proportion and the relative reproductive performance per ewe age group, this range is close to the minimum and maximum number of lambs tailed per ewe mated that is feasible and is consistent with the normal distribution pattern of lambing performance on New Zealand farms (Beef + Lamb New Zealand, n.d.).

When tested with all other parameters fixed as per the baseline model, increasing ewe lambing percentage from 110% to 170% increased whole-of-system feed conversion efficiency (FCE) by 19.2% (Figure 6.1). Whole-of-system feed requirements decreased by 11.9% during the ewe pregnancy period and decreased by 2% during lactation but increased by 11.2% during the post-weaning period (Figure 6.2; Table 6.1). Also, as lambing percentage increased, the proportion of lamb carcass to total meat carcass production increased considerably (from 76.1% to 83.3%) with the proportion of mutton carcass production reducing from 23.9% when lambing percentage was 110% to just 16.7% when lambing percentage was 170%.

As lambing percentage increased, the gain in FCE arose from spreading the maternal overhead feed cost across more lambs. However, as the number of lambs per ewe increased, the marginal change in FCE of the system declined. For example, when the number of lambs tailed per ewe mated increased from 110% to 120%, FCE increased 4%. When the number of lambs tailed per ewe mated increased from 160% to 170%, FCE increased only 2%.

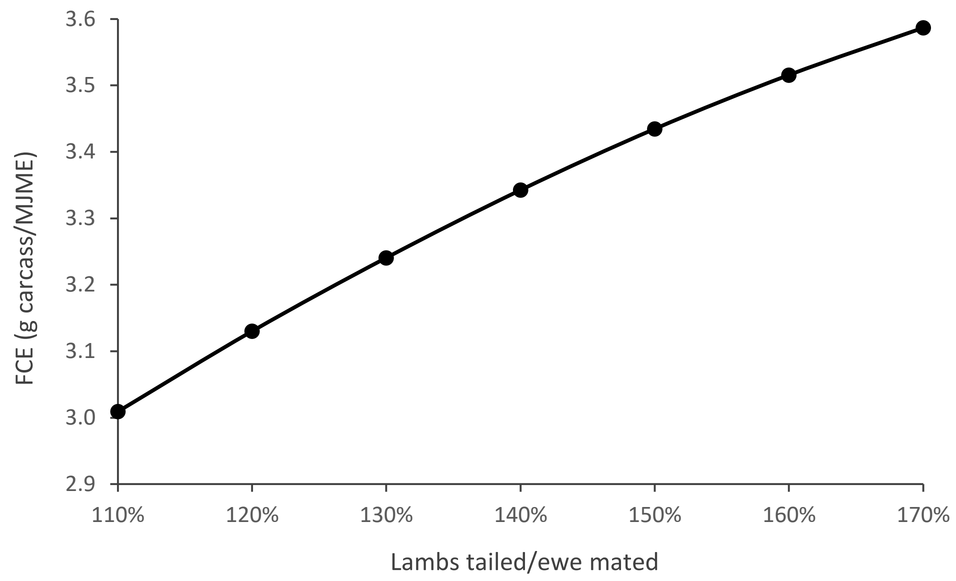


Figure 6.1 Relationship between ewe lambing percentage (lambs tailed per ewe) on the feed conversion efficiency (g carcass/MJME) of the sheep meat livestock production system

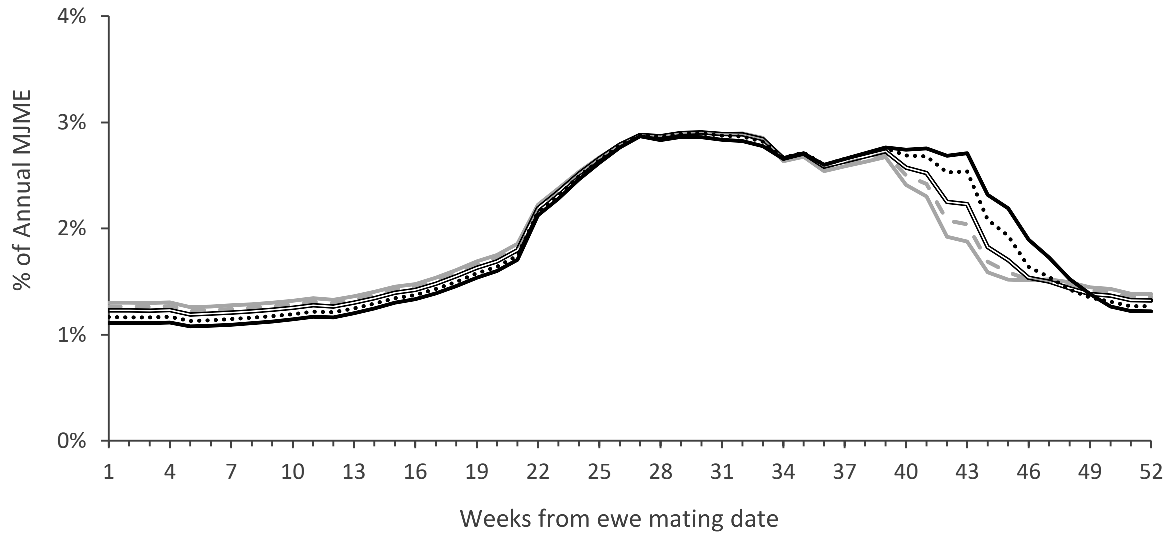


Figure 6.2 The effect of lambing percentage (lambs tailed per ewe mated) at five example lambing rates (——110% – – –120% (baseline) ═══ 130% ········· 150% —— 170%) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

When tested with all other parameters fixed as per the baseline scenario, the decline in the marginal gain in FCE with increasing lambing percentage was the result of increased pre-weaning lamb deaths and the lower lamb growth rate of twin and triplet lambs. For example, when the number of lambs tailed per ewe mated was 110%, the whole-of-flock average pre-weaning lamb death rate per lamb born (dead or alive) was 10.3% and the weighted average daily gain of all [sale] lambs from birth to sale was 248 g/day. Increasing the number of lambs tailed per ewe mated to 170% increased the whole-of-flock average lamb death rate per lamb born to 14.1% and decreased the weighted average daily gain of all lambs from birth to sale to 222 g/day. This decrease in the whole-of-flock average lamb growth rate was because of the greater proportion of twin and triplet lambs which had slower growth rates in comparison to single lambs. The effect of increased lambing percentage under different scenarios of lamb growth rate and lamb survival is tested in Chapter 7.

Reduced feed demand during the pregnancy period was a result of lower ewe numbers. For example, with total feed energy availability fixed, increasing the number of lambs tailed per ewe mated from 110% to 170% resulted in ewe numbers at mating date falling by 15.2% (Table 6.1).

Table 6.1 The effect of ewe lambing percentage (lambs tailed per ewe) on meat carcass output, stock numbers at ewe mating date and the percentage of total feed demand required during the periods of ewe pregnancy, lactation, and post-weaning

Lambing%	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
110%	30,092	76.1%	23.9%	1,352	280	29.7%	32.8%	37.5%
120%*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
130%	32,406	79.2%	20.8%	1,275	264	28.4%	32.7%	39.0%
140%	33,425	80.5%	19.5%	1,239	257	27.7%	32.6%	39.7%
150%	34,346	81.5%	18.5%	1,206	250	27.2%	32.5%	40.4%
160%	35,157	82.5%	17.5%	1,175	243	26.6%	32.3%	41.0%
170%	35,867	83.3%	16.7%	1,147	238	26.2%	32.1%	41.7%

*Baseline scenario

In comparison to the pregnancy period, there was only a very small decrease in whole-of-system feed demand in the lactation period. This was due to the fact that reduced feed demand as a result of lower ewe numbers was offset by increased lactation requirements per litter.

During the post-weaning period, whole-of-system feed demand increased with increasing lambing percentage due to the greater number of twin and triplet lambs which grow slower and were therefore on-farm for longer. For example, when the number of lambs tailed per ewe mated was 110%, the average time from birth to lamb sale was 146 days. This increased to 166 days when the number of lambs tailed per ewe mated was 170%. The effect of lambing percentage on post-weaning feed demand was particularly great after about week 40 (Figure 6.2).

As a result of lower ewe numbers and a higher number of lambs sold, increasing lambing percentage also impacted on the proportion of lamb and mutton carcass production (Table 6.1). When lambing percentage was increased from 110% to 170%, the percentage of lamb carcass to total meat carcass increased from 76% to 83%.

6.3 Pre-Weaning Lamb Growth Rate

Pre-weaning growth rates were defined in the model in relation to single lambs. Accordingly, to test the effect of pre-weaning lamb growth rate, the pre-weaning growth rate of single lambs of mixed gender (see section 4.3.10) was adjusted. The relative growth rates between lambs of different sex, rear rank and dam age at baseline levels is therefore maintained, but the absolute growth rates for all of these lamb categories will increase proportionally to the increase in growth rate for singles. When testing the impact of pre-weaning lamb growth, post-weaning growth rates were kept at baseline levels. However, in the baseline model, the exception was for replacement ewes lambs. For these lambs, post-weaning growth rate was such that lambs reached target weights by hogget mating.

Increasing pre-weaning lamb growth rate for singles from 250 g/day to 450 g/day increased feed conversion efficiency by only 0.6% (Figure 6.3). It had minimal impact on flock structures but there was a major shift in feed demand from the post-weaning period to the lactation period (Table 6.2; Figure 6.4). Overall, whole-of-system feed demand was largely unchanged in pregnancy, but increased 48.7% in lactation and decreased 33.9% post-weaning.

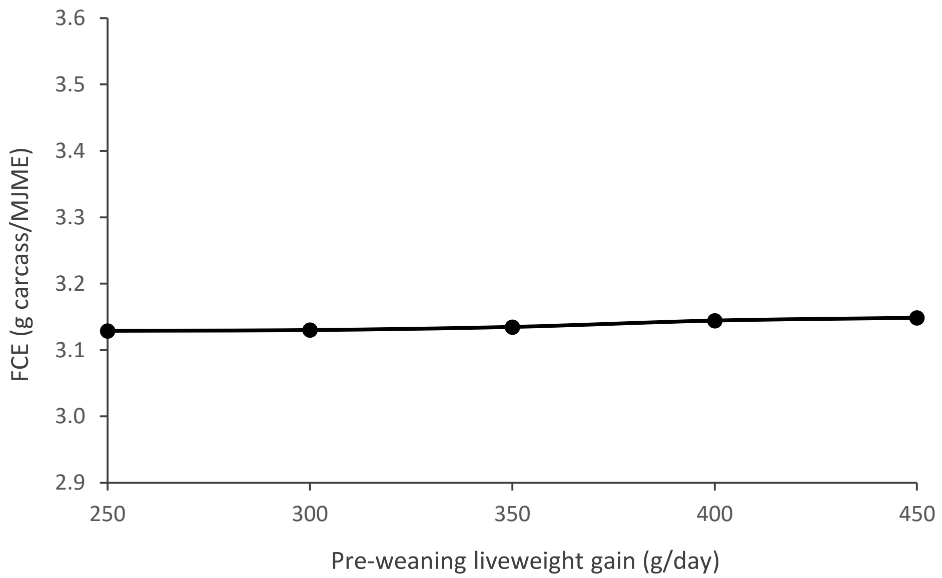


Figure 6.3 Relationship between pre-weaning lamb growth rate (g/day) and the feed conversion efficiency (g carcass/MJME) of the sheep livestock system

The higher feed demand required during lactation was the result of the increased energy demand for lamb maintenance and growth (and milk production). The lower feed demand required during the post-weaning period (and also in the first few weeks of the pregnancy period) was the result of earlier kill dates for lambs.

Table 6.2 The effect of pre-weaning growth rate (g/day) on meat output, stock numbers at ewe mating date and the percentage of annual feed demand required during key management periods

Pre-Wng LWG (g/day)	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
250	31,290	77.8%	22.2%	1,313	272	29.1%	29.3%	41.5%
300*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
350	31,348	77.8%	22.2%	1,315	272	29.0%	36.5%	34.6%
400	31,444	77.8%	22.2%	1,319	273	29.0%	40.5%	30.5%
450	31,486	77.8%	22.2%	1,321	274	28.9%	43.6%	27.4%

*Baseline scenario

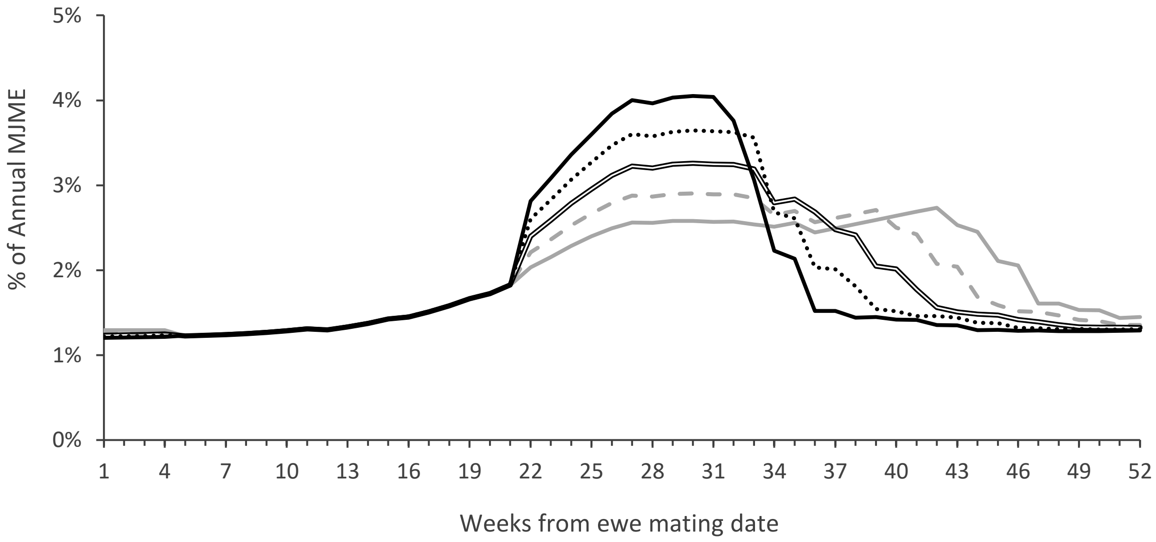


Figure 6.4 The effect of pre-weaning liveweight gain of lambs (—— 250 g/day – – – 300 g/day (baseline) ══ 350 g/day ••••••••• 400 g/day —— 450 g/day) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

6.4 Post-Weaning Lamb Growth Rate

In comparison to pre-weaning growth rate, post-weaning lamb growth rate did have an impact on whole-of-system feed conversion efficiency (Figure 6.5). This effect was curvilinear and whereas feed conversion efficiency increased by 3.9% when post-weaning lamb growth rate increased from 100 g/day to 150 g/day, the increase was only 0.8% when these growth rates were increased from 250 g/day to 300 g/day. Overall, feed conversion increased by 7.8% when the post-weaning lamb growth rate was increased from 100 g/day to 300 g/day.

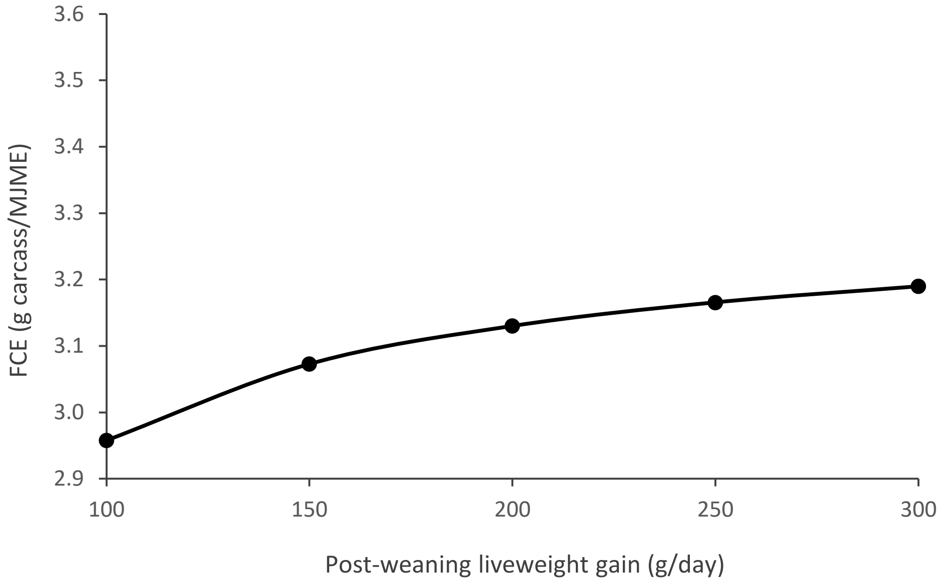


Figure 6.5 Relationship between post-weaning lamb growth rate (g/day) and the feed conversion efficiency (g carcass/MJME) of the sheep livestock system

Efficiency gains were a result of lower maintenance energy costs as a consequence of earlier lamb kill dates which allowed an increase in ewe numbers and hence lambs, which increased in direct proportion to the gain in feed conversion efficiency (Table 6.3). As with pre-weaning lamb growth rate, post-weaning growth rate had no effect on the ratio of lamb to mutton carcass production (Table 6.3).

Table 6.3 The effect of post-weaning growth rate (g/day) on meat output, stock numbers and the proportion of annual feed demand required during key management periods

Post-Wng LWG (g/day)	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
100	29,577	77.8%	22.2%	1,241	257	29.7%	30.9%	39.4%
150*	30,728	77.8%	22.2%	1,289	267	28.8%	32.1%	39.1%
200	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
250	31,656	77.8%	22.2%	1,328	275	29.3%	33.1%	37.6%
300	31,898	77.8%	22.2%	1,338	277	29.6%	33.4%	37.1%

*Baseline scenario

Increasing post-weaning lamb growth rate from 100 g/day to 300 g/day increased the whole-of-system feed demand 7.8% in lactation but decreased whole-of-system feed demand 5.9% post-weaning (Table 6.3). However, while overall feed demand in the post-weaning period reduced as a result of the earlier kill date of lambs, feed demand increased in the weeks immediately following weaning (from week 34) as a result of higher lamb energy requirements for liveweight gain and maintenance (Figure 6.6).

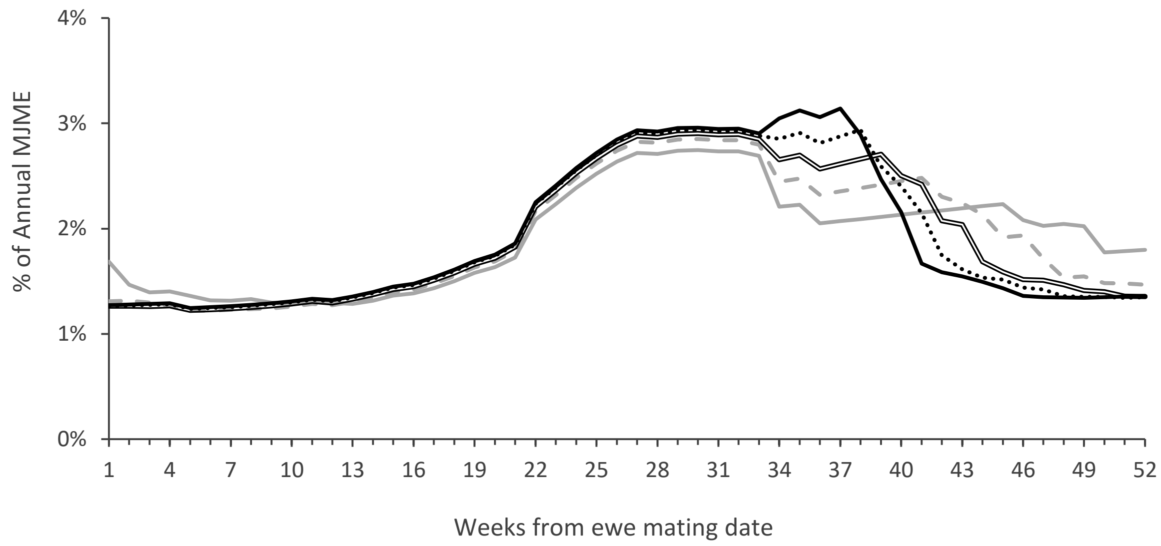


Figure 6.6 The effect of post-weaning liveweight gain of lambs (—— 100 g/day – – – 150 g/day ═══ 200 g/day (baseline) ········· 250 g/day —— 300 g/day) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

Overall, there was only a small impact on whole-of-system feed demand during the pregnancy period. This was because although ewe numbers increased with higher post-weaning lamb growth rates, higher feed demands from these ewes were offset by reduced energy requirements for tail-end lambs, which, at very low growth rates, was considerable. For example, when post-weaning growth rate was 100 g/day, 660 sale lambs were still on-farm at ewe mating date, thus increasing whole-of-system energy demand during the pregnancy period. In contrast, when post-weaning growth rate was increased to 300 g/day all sale lambs were slaughtered prior to ewe mating date.

6.5 Ewe Size

The effect of ewe size on feed conversion efficiency and the seasonality of feed demand was tested by modelling a range of ewe liveweights from 50 kg to 80kg which represents the range of ewe sizes (as genetically determined) common to New Zealand sheep breeds (Meadows, 2008). There are two underlying assumptions of note in relation to the following experimentation on ewe size. The first is that both ewe reproductive performance and lamb growth rate (and milk production) were assumed as independent from ewe size. For example, changes to ewe size did not result in corresponding changes to lambing percentage or lamb growth rate. The effect of ewe size under varying lambing rates and lamb growth rates are tested in Chapter 7. The second assumption is that the mature size of lambs was assumed to be a function of the size of the ewe. The implications of these two assumptions are discussed in following sections.

When tested with all other parameters fixed as per the baseline model, increasing ewe size from 50 kg to 80 kg decreased whole-of-system feed conversion efficiency by 8.3% (Figure 6.7). Overall, whole-of-system feed demand increased 15.5% during pregnancy, decreased 11.9% during lactation and remained approximately unchanged in the post-weaning period (Figure 6.8; Table 6.4).

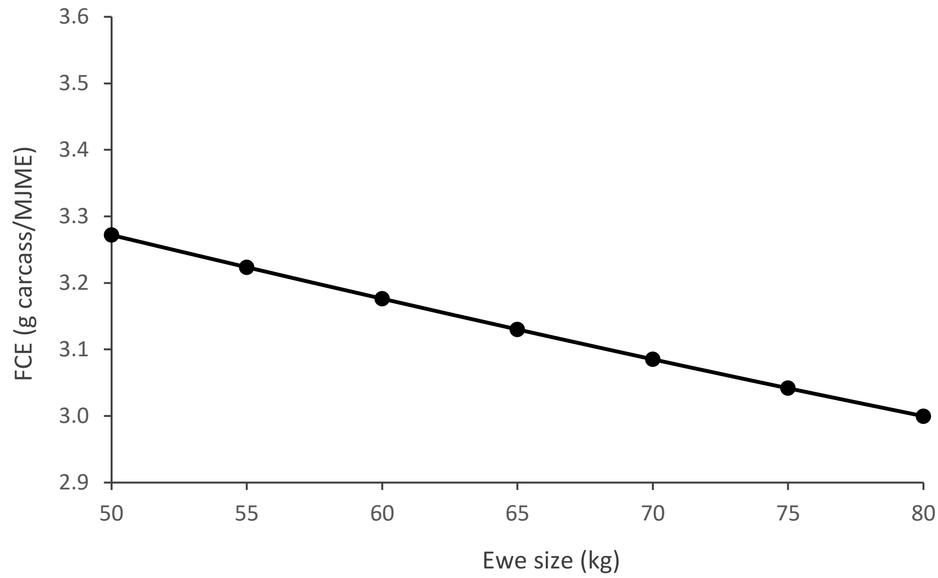


Figure 6.7 Relationship between ewe size (kg) and the feed conversion efficiency (g carcass/MJME) of the sheep meat livestock production system

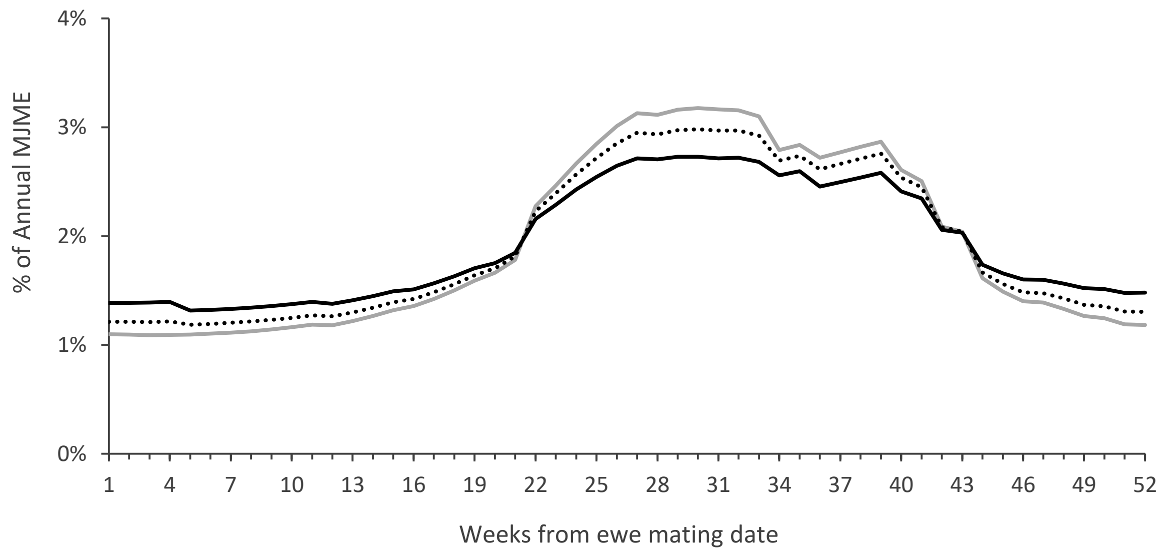


Figure 6.8 The effect of ewe size (kg liveweight) at three example weights (—— 50 kg ········ 65 kg (baseline) —— 80 kg) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

The negative relationship between ewe size and whole-of-system feed conversion efficiency of the sheep livestock system was because, when ewes were heavier, higher maintenance energy requirements increased the feed demand per ewe. Assuming a fixed supply of feed, this required a reduction in ewe numbers which subsequently reduced the number of ewes culled, reduced the number of lamb born (and sold) and decreased total meat carcass output. The relationship between ewe size and ewe numbers was approximately linear with total ewe numbers reducing 17.9% when ewe size was increased from 50 kg to 80 kg (Table 6.4).

Table 6.4 The effect of ewe size (kg) on meat output, stock numbers and the % of annual feed demand required during key management periods

Ewe Size (kg)	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
50	32,720	82.3%	17.7%	1,453	301	26.6%	35.3%	38.1%
55	32,236	80.7%	19.3%	1,404	291	27.5%	34.3%	38.2%
60	31,763	79.2%	20.8%	1,357	281	28.3%	33.5%	38.2%
65*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
70	30,851	76.3%	23.7%	1,271	263	29.7%	32.1%	38.2%
75	30,416	75.0%	25.0%	1,230	255	30.2%	31.6%	38.2%
80	29,997	73.7%	26.3%	1,192	247	30.7%	31.1%	38.2%

* Baseline scenario

Despite lower ewe and hogget numbers, increased ewe size increased whole-of-system feed demand during the pregnancy period as a result of the higher maintenance energy costs per ewe. In contrast, increased ewe size decreased whole-of-system feed demand during lactation. This was because the energy savings from lower lactation requirements (linked to lower ewe numbers) outweighed the higher energy costs for maintenance. Also, as the mature size of lambs was linked to ewe size, at the same liveweight, lambs had a lower rate of fat deposition and required less energy per kg of liveweight gain.

While the overall effect of increasing ewe size resulted in a small increase in whole-of-system feed demand in the post-weaning period, in the first 11 weeks of the post-weaning period, higher ewe size resulted in lower weekly feed demands. This was because the lower feed demand from reduced stock numbers outweighed the higher maintenance energy costs of heavier ewes. However, as individual groups of lambs reached target slaughter weight and were sold, the effect of higher maintenance requirement of ewes was more evident. At week 44 the energy savings as a consequence of lower ewe numbers was equal to the extra energy required for ewe maintenance. Past week 44, increased ewe size resulted in higher weekly feed energy costs.

As a consequence of the heavier individual carcass weight of cull ewes, increasing ewe size also increased the proportion of mutton carcass production (Table 6.4). When ewe size was increased from 50 kg to 80 kg, the proportion of mutton to total meat carcass production increased from 18% to 26%.

6.6 Carcass Weight

When carcass weight was tested against baseline values for all other parameters, increasing target carcass weight from 12 kg to 24 kg increased feed conversion efficiency by 28% (Figure 6.9). This efficiency benefit was due to the increased meat carcass output per lamb and lower ewe maintenace energy overheads per kg meat produced. However, there were declining additional efficiency benefits from each additional kg increase. For example, whereas feed conversion efficiency increased by 3.5% when carcass weight increased from 12 kg to 13 kg, the increase was only 1% when carcass weight was increased from 24 kg to 25 kg. A 1 kg increase from the current 18 kg average New Zealand carcass weight (Beef + Lamb New Zealand Economic Service, 2016, p. 15) to 19 kg increased feed conversion efficiency by 1.9%.

This curvilinear relationship and the decrease in the marginal gain in feed conversion efficiency was due to a number of factors. The primary reason why the marginal gain in feed conversion efficiency declined with each successive unit of carcass weight gain was a consequence of changes in the composition of liveweight gain and an associated increase in the energy requirement per kg of liveweight gain. A second reason was that the additional benefits of spreading the maternal overhead costs per lamb declined with each successive unit increase in carcass weight.

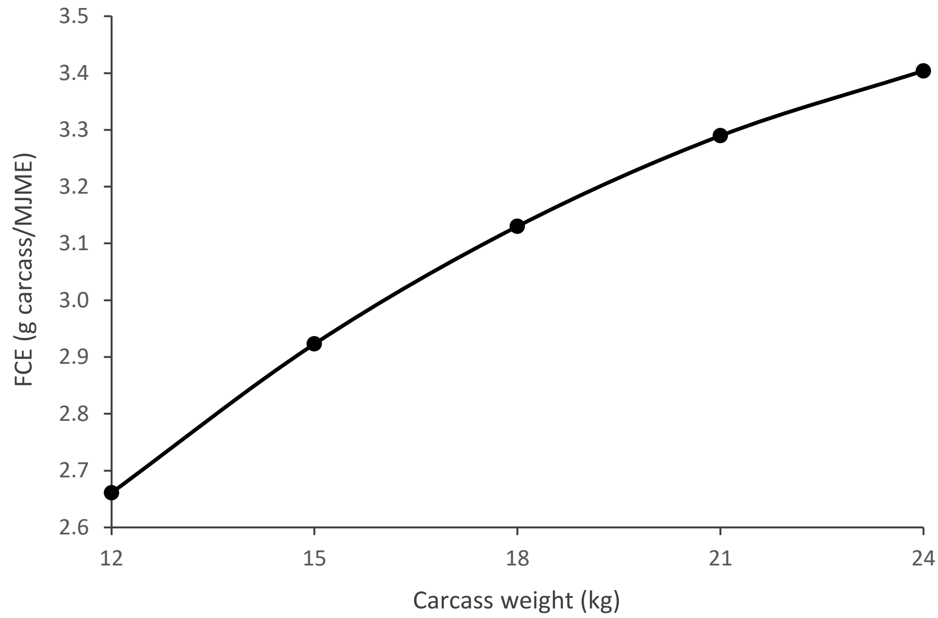


Figure 6.9 Relationship between lamb carcass weight (kg) and the feed conversion efficiency (g carcass/MJME) of the sheep livestock production system

As carcass weight increases, and within a fixed total supply of feed energy, there was a decline in the number of ewes that could be carried (Table 6.5). This relationship between carcass weight and ewe numbers was approximately linear with each kg increase in carcass weight requiring ewe numbers to decrease by approximately 2.4%. As a consequence of this reduction in ewe numbers, increasing lamb carcass weights had a large impact on the proportion of lamb to mutton carcass with the proportion of lamb carcass to total meat carcass increasing from 70% to 82% when lamb carcass weight was increased from 12 kg to 24 kg.

Table 6.5 The effect of lamb carcass weight (kg) on meat output, stock numbers and the percentage of annual feed demand required during pregnancy, lactation and post-weaning

Carcass Weight (kg)	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
12	26,607	70.0%	30.0%	1,507	312	33.3%	36.5%	30.2%
15	29,230	74.4%	25.6%	1,409	292	31.1%	35.1%	33.8%
18*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
21	32,896	80.3%	19.7%	1,222	253	27.3%	30.5%	42.2%
24	34,040	82.3%	17.7%	1,134	235	26.8%	28.3%	44.9%

*Baseline scenario

In relation to whole-of-system feed demand seasonality, carcass weight had a major effect. Heavier carcass weights resulted in a transfer of feed from the pregnancy and lactation period to the post-weaning period (Table 6.5; Figure 6.10). Lower feed requirements in the pregnancy and lactation periods were due to the large reduction in ewe numbers that were required to ensure total system feed requirements remained constant. However, at very heavy carcass weights, and assuming lamb growth rates remain at baseline levels, system feed demand did increase in the early pregancy period. This was a consequence of the increased time that was required for lambs to reach slaughter

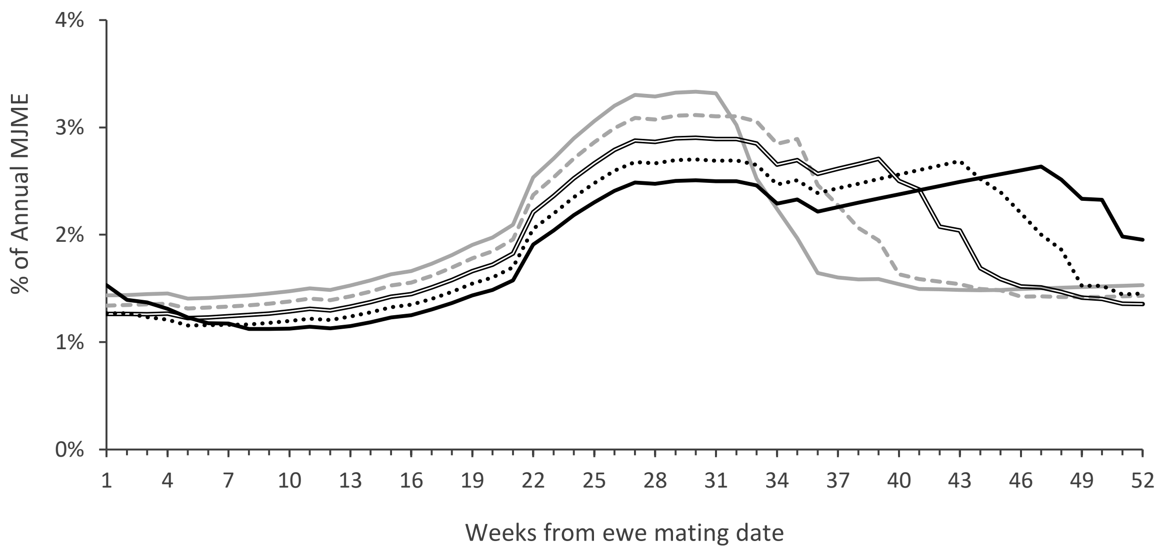


Figure 6.10 The effect of lamb carcass weight (—— 12 kg – – – 15 kg ═══ 18 kg (baseline) ········ 21 kg —— 24 kg) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

weights. Also, in the post-weaning period, although feed demands were lower in the weeks immediately following weaning (as a result of reduced ewe and hence lamb numbers), higher carcass weights dramatically increased feed demand thereafter. This was due to the increased time required for lambs to reach slaughter weight. For example, when target carcass weight was 12 kg, the average time from birth to lamb sale was 87 days. When carcass weight was 24 kg, this increased to 212 days. Overall, when carcass weight was increased from 12 kg to 24 kg, whole-of-system feed demand decreased by 19.5% during the ewe pregnancy period, decreased by 22.6% during the lactation period and increased 48.8 % during the post weaning period.

6.7 Hogget Lambing

Hogget lambing, defined as the number of lambs[7] tailed per total hogget, is the result of a number of variables including the proportion of hoggets mated, the proportion of mated hoggets that do not conceive (the dry rate), and the number of lambs born per hogget lambing (the litter size). Scenarios of mating percentage, dry rate and litter size used to test the effect of hogget lambing on feed conversion efficiency and the seasonality of feed demand are shown in Table 6.6. In these scenarios, assumptions relating to lamb survival were kept at baseline levels.

Table 6.6 Percentage of lambs tailed per total hogget under the different scenarios of hogget mating and reproductive performance per hogget mated

Scenario	Hoggets Mated	Dry Rate per Hogget Mated	Litter Size per Hogget Lambing	Hogget Lambing Percentage (Lambs tailed per Total Hogget)
1.	0%	NA	NA	0%
2.	50%	44%	110%	30%
3. (Baseline)	100%	44%	110%	60%
4.	100%	25%	125%	90%
5.	100%	10%	140%	120%

Increasing hogget lambing from 0% to 120% increased feed conversion efficiency by 10% (Figure 6.11). This increase in efficiency was the result of spreading the feed overhead costs for feeding replacement hoggets across more output. When hogget lambing increased from 0% to 120% total ewe numbers (aged 2-tooth and older) reduced by 7.4%. There was also a small change in the proportion of lamb to mutton carcass with an increase from 76% to 79% (Table 6.7).

Overall, hogget lambing had a small but measureable effect on the seasonal timing of feed demand (Figure 6.12). Increasing hogget lambing from 0% to 120% reduced whole-of-system feed demand 5%

[7] Born to hogget dams

during the ewe pregnancy period, reduced whole-of-system feed demand 1.9% during ewe lactation and increased whole-of-system feed demand 5.7% during the post-weaning period.

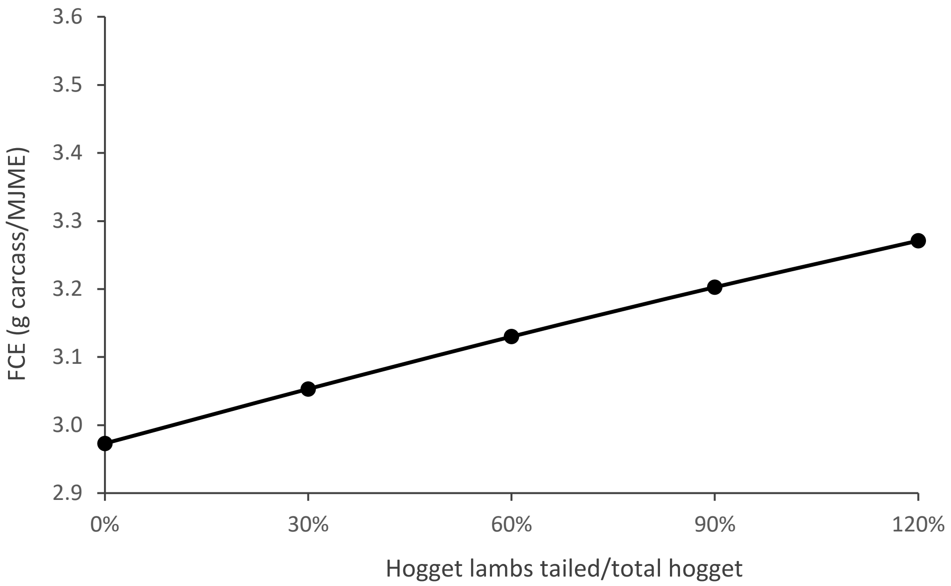


Figure 6.11 Relationship between hogget lambing (hogget lambs tailed per total hogget) scenarios and the feed conversion efficiency (g carcass/MJME) of the sheep livestock production system

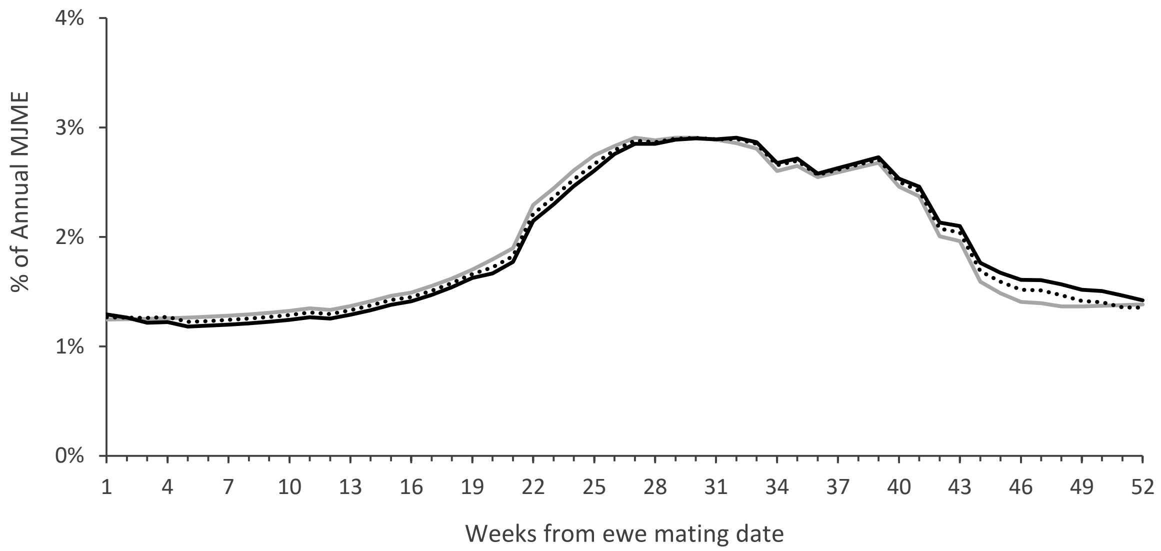


Figure 6.12 The effect of hogget lambing (hogget lambs tailed per total hogget) for three example scenarios (—— 0% ········· 60% (baseline) —— 120%) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

Table 6.7 The effect of hogget lambing on meat output, stock numbers and the % of annual feed demand required during key management periods

Hogget Lambing	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
0%	29,730	75.6%	24.4%	1,367	283	29.7%	33.1%	37.2%
30%	30,532	76.7%	23.3%	1,339	277	29.4%	32.9%	37.7%
60%*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
90%	32,027	78.7%	21.3%	1,289	267	28.6%	32.6%	38.8%
120%	32,711	79.5%	20.5%	1,266	262	28.2%	32.4%	39.3%

*Baseline scenario

6.8 Age of Culling

To test the effect of ewe longevity, the age in which ewes were culled was increased from 5.3 years of age to 10.3 years of age. At the lower limit of 5.3 years of age, ewes had the opportunity to have a total of four lambings as a ewe or five lambings if mated as a hogget. If the cull age was increased to 10.3 years of age then ewes had the opportunity to have a total of nine lambings as a ewe or 10 lambings if mated as a hogget. A maximum age of 10 years was chosen as Johnston (1983, p. 2) reports that this is the natural lifetime of sheep. As cull age was increased, ewe mortality and reproductive performance per ewe was assumed to remain at baseline levels. However, in the baseline assumptions, ewe lambing percentage and ewe mortality was related to age (see sections 4.3.4 and 4.3.7). Therefore, delaying cull age reduced flock average lambing percentage and increased whole-of-flock mortality rates.

When the age of ewe culling was increased from 5.3 years of age to 6.3 years of age there was a very small increase in feed conversion efficiency (Figure 6.13; Table 6.8). However, when cull age was greater than 6.3 years of age, the overall feed conversion efficiency declined, albeit by a small amount. Overall, increasing the age of ewe culling from 5.3 years to 10.3 years resulted in a 3.2% reduction in whole-of-system feed conversion efficiency.

When ewes were culled at a young age, increasing ewe longevity had a positive effect on feed conversion efficiency because the longer ewes were kept for breeding, fewer lambs were required to be retained for replacements and more lambs can be sold. For example, increasing the age of culling from 5.3 years to 10.3 years reduced the number of hogget replacements by 40.1%. As less energy was required to feed replacement animals, the total number of breeding ewes could increase, thus increasing the number of lambs born and sold (Table 6.8).

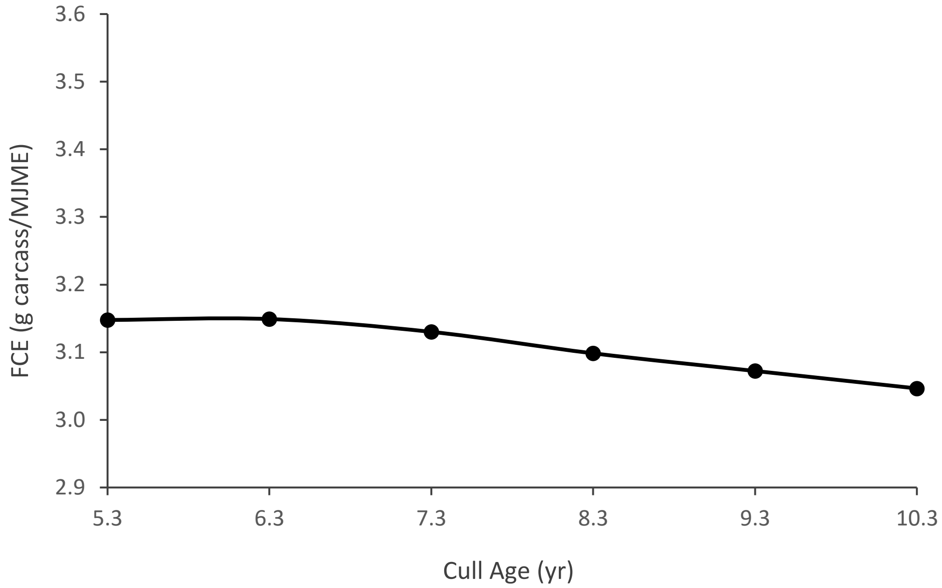


Figure 6.13 The effect of cull age (in years at the date of culling) on the feed conversion efficiency (g carcass/MJME) of the sheep meat livestock production system

However, as the average age of the breeding flock increased, higher mortality in older age groups resulted in higher total deaths. This subsequently meant that, of the total breeding ewes that were kept, fewer could be sold for mutton at culling date. This reduction in meat carcass output from mutton outweighed the savings in feed costs from lower numbers of replacement lambs and hoggets and therefore reduced whole-of-system feed conversion efficiency as the age of ewe culling increased beyond 6.3 years.

Table 6.8 The effect of age of culling on meat output, stock numbers and the % of annual feed demand required during key management periods

Cull Age (Years)	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
5.3	31,477	69.5%	30.5%	1,258	359	29.6%	32.3%	38.1%
6.3	31,490	74.5%	25.5%	1,288	307	29.2%	32.6%	38.2%
7.3*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
8.3	30,984	80.2%	19.8%	1,335	247	29.0%	32.8%	38.2%
9.3	30,723	82.0%	18.0%	1,353	229	28.9%	32.9%	38.2%
10.3	30,465	83.4%	16.6%	1,368	215	28.9%	33.0%	38.1%

*Baseline scenario

As ewe longevity and the age of ewe culling was increased, the increase in ewe deaths and hence reduction in the proportion of ewes that could be sold as cull animals, combined with an increased in the proportion of total lambs that could be sold (due to lower numbers retained for breeding), dramatically increased the proportion of lamb carcass to total carcass production (Table 6.8). For example, when cull age was increased from 5.3 years to 10.3 years, the proportion of lamb carcass to total meat carcass increased from 68% to 83%.

Increasing cull age from 5.3 to 10.3 years of age had only a small impact on the seasonality of feed demand with whole-of-system feed demand decreasing 3% during ewe pregnancy, increasing 1.5% during the lactation period, and increasing 1.1% during the post-weaning period (Figure 6.14; Table 6.8).

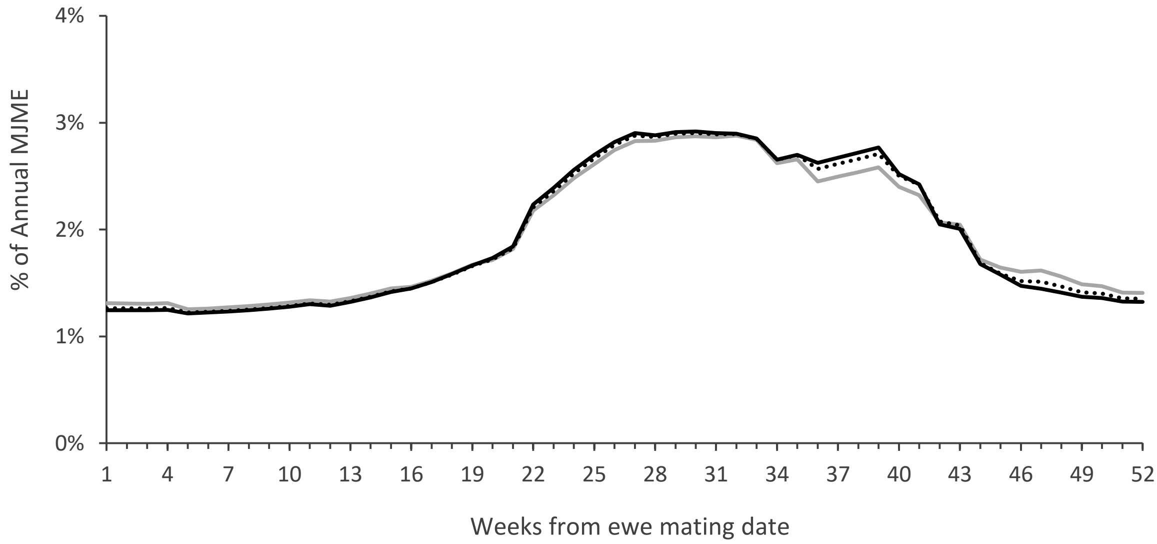


Figure 6.14 The effect of cull age (in years at the date of culling) for three example culling ages (—— 5.3 years •••••••• 7.3 years (baseline) —— 10.3 years) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

Higher feed demand during the early part of the post-weaning period (from week 34 to 42) was due to an increased number of lambs, consequent to higher ewe numbers, and the small increase in flock average lamb growth rates, due to the greater proportion of lambs born to MA ewes and the higher growth rates of these lambs in comparison to lambs born to younger ewes or hoggets.

Lower feed demand in the latter part of the post-weaning period (from week 44) was due to the reduced number of lambs retained for replacements combined with the fact that, due to lower hogget numbers, there were fewer lambs born to hoggets, which were slower growing in comparison to lambs born to older ewes and took longer to reach target slaughter weight.

6.9 Ewe Mortality

The effect of mortality rate was tested by increasing the mortality rate of mid-aged ewes (4 tooth to 6yr ewes) while keeping the relative mortality rate between this age group and hoggets, 2-tooth ewes and old ewes (7year ewes and older) at baseline levels. Accordingly, although the input parameter for ewe mortality was relative to a specific age group (mid-aged ewes) it resulted in a proportional increase in the mortality of all age groups.

Increasing the mortality rate of mid-aged ewes from 1% to 7% reduced whole-of-system feed conversion efficiency by 7.6% (Figure 6.15). While there was no change in the number of ewes at mating date, the number of hoggets increased by 14.1%. There was also a change in the proportion of lamb and mutton carcass production with the proportion of lamb to total carcass increasing from 77% to 79% (Table 6.9). When the mortality rate of mid-aged ewes was increased from 1% to 7%, whole-of-system feed demand increased 2% during pregnancy, decreased 1.6% during lactation and was unchanged in the post-weaning period (Figure 6.16; Table 6.9).

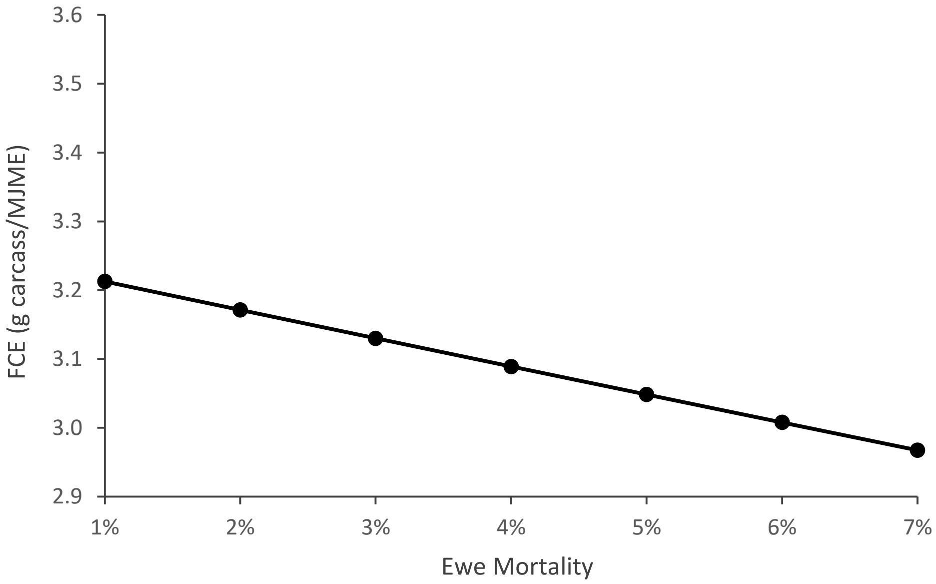


Figure 6.15 Relationship between ewe mortality rate (deaths as a percentage of ewes at mating date) on the feed conversion efficiency (g carcass/MJME) of the sheep meat livestock production system

As mortality increased, the loss in system feed efficiency was due to the decrease in the proportion of total ewes that could be sold at culling date which therefore decreased total meat carcass output. As a proportion of ewe losses occurred prior to lambing date, higher mortality rate also decreased the number of lambs born and sold. For example, increasing mortality rate of mid-aged ewes from 1% to 7% reduced the whole-of-flock lambing percentage (lambs tailed per ewe mated) by 3.5%. Also, as mortality rate increased, a greater number of ewe lambs were required for replacements which further reduced lamb meat output as a consequence of the reduced proportion of total lambs slaughtered. In total, and despite increased hogget numbers and the increase in the number of lambs from hoggets, 5.4% less lambs were sold when the mortality rate was increased from 1% to 7%.

During the pregnancy period, increased mortality led to increased feed demand (albeit by a very small amount) due to the increase in the proportion of hoggets required for replacements and due to the fact that hoggets had higher feed demands consequent to a higher energy requirement for liveweight gain.

Table 6.9 The effect of the mortality rate (%) of breeding females on meat output, stock numbers and the % of annual feed demand required during key management periods

Mortality %	Meat Carcass (kg)	% Lamb	% Mutton	Ewes	Hgts	% Annual MJME		
						Pregnancy (wk 1-21)	Lactation (wk 22-33)	Post-Wng (wk 34-52)
1%	32,126	77.1%	22.9%	1,314	260	28.8%	32.9%	38.2%
2%	31,713	77.4%	22.6%	1,313	266	28.9%	32.8%	38.2%
3%*	31,301	77.8%	22.2%	1,313	272	29.0%	32.7%	38.2%
4%	30,891	78.1%	21.9%	1,312	278	29.1%	32.6%	38.2%
5%	30,483	78.4%	21.6%	1,312	284	29.2%	32.6%	38.2%
6%	30,077	78.7%	21.3%	1,311	291	29.3%	32.5%	38.2%
7%	29,673	79.0%	21.0%	1,310	297	29.4%	32.4%	38.2%

*Baseline scenario

Despite the higher number of hoggets, lower whole-of-system feed demand during the lactation and early post-weaning periods were due to the reduction of feed energy requirement from ewes that died. The increase in whole-of-system feed demand during the last few weeks of the post-weaning period was because of the higher proportion of lambs retained for replacements.

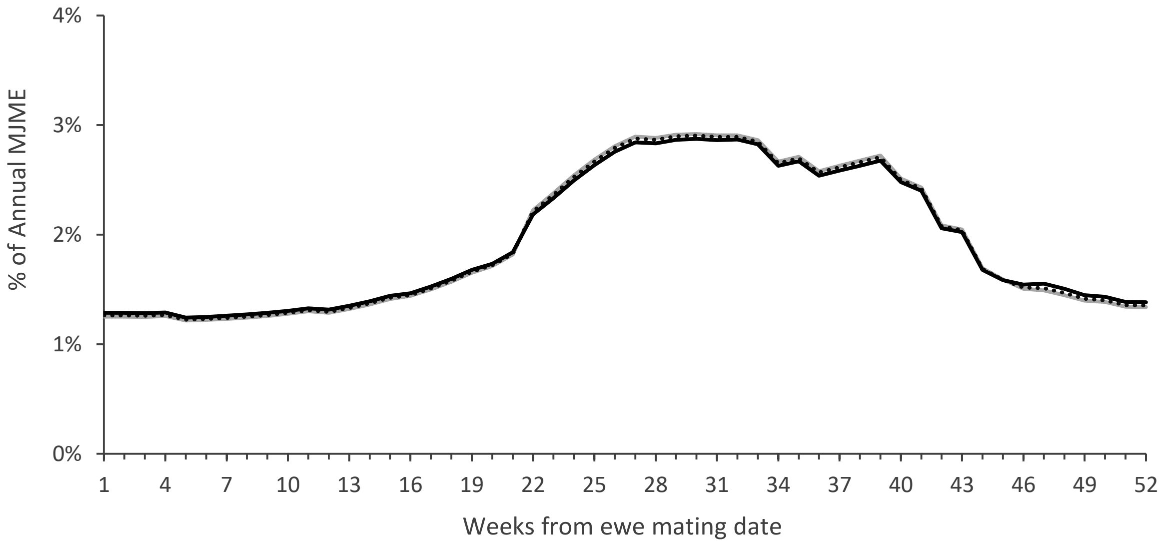


Figure 6.16 The effect of ewe mortality rate (deaths as a percentage of ewes at mating date) for three example rates (—— 1% ········· 3% (baseline) —— 7%) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

6.10 Validation of Model Results

In relation to single-factor experimentation the same verification (internal validation) issues that were discussed in Chapter 5 apply. However, external validation is an ongoing process and relates to purpose (Daellenbach & McNickle, 2005, p. 121). Each chapter has its own purpose. In the previous chapter, to increase the confidence in the model, absolute feed conversion efficiency of the baseline livestock model was compared to similar research. However, rather than measuring feed conversion efficiency in absolute terms, the purpose of this chapter is to provide percentage changes in feed conversion efficiency outcomes relative to percentage changes in key decision variables. Therefore, from now on, the aim of model validation is to establish confidence and credibility that the model sufficiently captures the relative changes in feed conversion efficiency with changes in input variables. In this chapter, key validation issues relate to the sensitivity of birth rank proportions and survival rates of multiple born lambs to the relative impact of lambing percentage; the sensitivity of lamb energy requirements to the relative impact of lamb growth rate; the sensitivity of DO% to the relative impact of lamb growth and target carcass weight; the sensitivity of the maintenance energy requirement of ewes to the relative impact of ewe size; the sensitivity of the standard reference weight of lambs to the relative impact of ewe size; and the sensitivity of the energy requirement for liveweight gain to the relative impact of lamb carcass weight.

A discussion of validation issues arising from interrelationships and system dependencies between lambing percentage, lamb growth rate, ewe size, carcass weight, hogget lambing, cull age and ewe mortality is deferred until Chapter 7.

Sensitivity of lamb birth rank proportions and survival rates of multiple born lambs to the relative impact of lambing percentage

In the base model, the proportion of ewes with single, twin and triplet litters relative to average flock lambing percentage was based on whole flock observations of traditional New Zealand breeds by Davis et al. (1983). However, for a given flock lambing percentage there could be a large range of feasible birth rank proportions especially for prolific sheep breeds such as the Finn and East Friesian (Davis, 2004). This may have an impact on the relative effect of whole-of-flock lambing percentage on feed conversion efficiency. To test this, the proportion of twin lambs was increased (at the expense of single and triplet lambs) to the maximum proportion allowable. For example, at the highest lambing percentage of 170% lambs tailed per ewe mated, the proportion of twin lambs was increased to 89% with just 11% being single lambs and no lambs being triplets. This compares to the base assumptions where 17% of lambs were single, 61% were twins, and 22% were triplets. However, this increase in the proportion of twin lambs only increased feed conversion efficiency by 2.8% (from 3.59 g carcass/MJME to 3.69 g carcass/MJME). While this demonstrates that the benefits of a specific high lambing rate are, to a minor extent, modified by increasing the number of twins as a proportion of total births, this does not refute the generalised findings that increased lambing percentage will increase feed conversion efficiency (Section 6.2).

When all other parameters remained at baseline levels, reducing the lamb mortality rate of twin and triplet lambs by 5 percentage points (from 12% to 7% for twins and from 25% to 20% for triplets) increased feed conversion efficiency by 1.2%. However, at the maximum lambing percentage of 170% lambs tailed per ewe mated, reducing the mortality rate of multiple born lambs by 5 percentage points increased feed conversion efficiency by 2.2%. Inversely, increasing the mortality rate of multiple born lambs by 5 percentage points (from 12% to 17% for twins and from 25% to 30% for triplets) reduced feed conversion efficiency by 2.2%. Also, still assuming a 170% lambing percentage, when the mortality rate of twin and triplet lambs was assumed to be equal to that of single lambs (10%), feed conversion efficiency increased to 3.69 g carcass/MJME, a 2.8% increase in feed conversion efficiency relative to the baseline assumptions for lamb mortality.

Sensitivity of lamb energy requirements to the relative impact of lamb growth rate

Table 6.10 shows the sensitivity of maintenance, growth and lactation energy requirements to the relative impact of lamb growth rate (pre-weaning and post-weaning) on feed conversion efficiency (g carcass/MJME).

Table 6.10 Sensitivity of maintenance, growth and lactation energy requirements to the relative impact of lamb growth rate on feed conversion efficiency (g carcass/MJME)

	Pre-Wean LWG Parameter			Post-Wean LWG Parameter		
	250 g/day	450 g/day	% Change	100 g/day	300 g/day	% Change
Base model	3.13	3.15	0.6%	2.96	3.19	7.8%
-10% ME m (post-weaning)	3.16	3.16	0.0%	3.00	3.21	7.1%
+10% ME m (post-weaning)	3.10	3.14	1.2%	2.92	3.17	8.6%
-10% ME g (post-weaning)	3.16	3.16	-0.2%	2.98	3.22	8.0%
+10% ME g (post-weaning)	3.10	3.14	1.5%	2.93	3.16	7.7%
-10% NE m (pre-weaning)	3.12	3.17	1.7%	2.95	3.18	7.8%
+10% NE m (pre-weaning)	3.08	3.11	1.3%	2.91	3.14	7.7%
-10% NE g (pre-weaning)	3.13	3.21	2.8%	2.97	3.20	7.8%
+10% NE g (pre-weaning)	3.07	3.07	0.3%	2.90	3.12	7.6%
-10% ME lactation (ewe+lamb)	3.14	3.23	2.9%	2.98	3.22	7.9%
+10% ME lactation (ewe+lamb)	3.05	3.06	0.2%	2.89	3.10	7.6%
-10% Milk	3.10	3.15	1.6%	2.94	3.17	7.8%
+10% Milk	3.09	3.13	1.3%	2.93	3.15	7.7%
-10 kg SRW	3.04	3.08	1.2%	2.89	3.11	7.6%
+10 kg SRW	3.14	3.19	1.8%	2.97	3.21	7.8%
Repl. Lambs with Baseline LWG	3.12	3.18	1.9%	2.96	3.19	7.8%

Sensitivity of DO% to the relative impact of lamb growth and target carcass weight

In the base model, it was assumed that the sale of lambs “off-mother” prior to weaning did not impact on lamb dressing-out percentage. This is in contrast to Kirton et al. (1984) who found that lambs sold off-mother prior to weaning had a 2 to 4 percentage point increase in dressing-out percentage in comparison to lambs sold post-weaning. However, when the base model was altered and the dressing-out percentage of lambs that reached target slaughter weights prior to the date of weaning was increased by 3 percentage points (from 45.8% to 48.8% for ewe lambs and from 43.5% to 46.5% for ram lambs), feed conversion efficiency only increased 1.5% under the maximum lamb growth scenario. Therefore, even with possible changes in dressing-out percentage, when pre-weaning lamb growth rate was changed independently from other system parameters, it did not significantly change whole-of-system feed conversion efficiency.

In the base model, dressing-out percentage was linked to carcass weight. It was assumed that higher carcass weight increased the dressing-out percentage. However, if dressing-out percentage was fixed at baseline levels, increasing carcass weight from 12 kg to 24 kg increased feed conversion efficiency by 24% rather than 28%. Consequently, although changes in dressing-out percentage do impact feed conversion efficiency, this was not a major factor driving the large increase in feed conversion efficiency as a result of changes in carcass weight.

Sensitivity of the maintenance energy requirement of ewes and the mature size of lambs to the relative impact of ewe size

When ewe size was decreased from 80 kg to 50 kg, increasing the maintenance energy requirement of ewes and hoggets by 10% was associated with an increase in the relative effect of ewe size with feed conversion efficiency increasing 10.1% (from 2.83 to 3.12 g carcass/MJME) compared to an increase of 9.1% (from 3.00 to 3.27 g carcass/MJEM) in the base model. Reducing the maintenance energy requirement of ewes and hoggets by 10% resulted a decrease in the relative effect of ewe size with feed conversion efficiency increasing 7.9% (from 3.19 to 3.44 g carcass/MJME) when ewe size was decreased from 80 kg to 50 kg.

Under a self-contained steady-state flock situation and assuming a pure-bred flock, it is justified in assuming that the liveweight of progeny is linked to ewe size. However, this assumption does not necessarily hold in all cases as artificial mating or the use of higher liveweight terminal sires can be used over a proportion of the flock. To test the impact of such a strategy, the baseline model was modified so that changes to ewe size did not automatically change the mature size of sale lambs. If mature weight of lambs of sale lambs was fixed at the maximum (100 kg for ram lambs and 80 kg for ewe lambs), decreasing mature ewe size from 80 kg to 50 kg increased feed conversion efficiency from 3.00 g carcass/MJME to 3.47 g carcass/MJME. This was a 1.7 fold increase in the relative improvement in feed conversion efficiency in comparison to the baseline model where mature liveweight of lambs was linked to ewe size. Consequently, it was not just the higher maintenance energy cost of higher liveweight that was important, but the genetic correlation and associated changes in the composition and energy requirements of liveweight gain that was a key factor in the feed conversion efficiency effect of ewe size.

Sensitivity of the energy requirement for liveweight gain to the relative impact lamb carcass weight

When the lamb energy requirement of liveweight gain (pre-weaning and post-weaning) was decreased by 10%, feed conversion efficiency increased from 2.71 g carcass/MJME when lamb carcass weight was 12 kg to 29.1% when lamb carcass weight was 24 kg. This compares to the base model where feed conversion efficiency increased from 2.66 to 3.40 g carcass/MJME when target carcass weight was increased from 12 kg to 24 kg.

The mature size parameter for both ram and ewe lambs was also tested for sensitivities to the relative impact of target carcass weight on feed conversion efficiency. When the mature size of lambs was increased by 10 kg, feed conversion efficiency increased from 2.68 g carcass/MJME when carcass weight was 12 kg to 3.46 g carcass/MJME when carcass weight was increased to 24 kg. A 10% decrease in the SRW of lambs (from 65 kg to 55 kg for ewe lambs and 81 kg to 71 kg for trade lambs) reduced feed conversion efficiency to 3.34 g carcass /MJME.

Summary

Overall, the results presented in this chapter are considered ‘explainable’. This is a key criterion for model validity and gives confidence in the model outputs. Confidence in model outputs is also increased due to the lack of major sensitivities of input assumptions to the relative impact of system parameters on whole-of-system feed conversion efficiency.

6.11 Discussion

6.11.1 The Effect of System Parameters on Feed Conversion Efficiency

Feed requirements of breeding females make up a large component of total feed demands. These feed requirements can be considered an overhead cost of production. Accordingly, as ewe and hogget lambing percentage and carcass weights increase, these maternal overheads are spread across more production, consequently improving feed conversion efficiency. Also, assuming there were no change in productive output, reduced ewe size also decreased the maternal feed overhead and resulted in a considerable improvement in feed conversion efficiency. These principles have been understood for a long time, and the results of this study are broadly consistent with previous findings from Large (1970), Cruickshank et al. (2008;2009), and Rutherford et al. (2003). They are also comparable with alternative livestock species (Woodford, 1997).

However, in relation to lambing percentage and carcass weight, what was notable was the extent to which additional feed conversion efficiency benefits declined from additional increases in lambing percentage and carcass weight. This finding is similar to that of Cruickshank et al. (2009) who noted that changes in livestock production parameters do not necessarily result in cumulative reductions in the methane output of the sheep flock. Such system dynamics therefore highlight the importance of taking a systems approach to analysing efficiency changes.

In relation to a fixed total supply of feed, the overall system benefits tended to be lower than was superficially apparent from consideration of system components. For example, whereas an increase in lambing from 110% to 170% increased the number of lambs per ewe by 54.5% (0.6 ÷ 1.10), the increase in overall system feed conversion efficiency was only 19.2%. Similarly, whereas increasing carcass weight from 12 kg to 24 kg increased lamb output per ewe by 100%, the system improvement in meat production was only 28%. Accordingly, it is clear that major productivity improvements require a focus on multiple parameters of the system.

Lambing Percentage

In a modelling study of the feed demand and efficiency of different sheep breeds, Brookes et al. (1998) observed that sheep breeds with higher lambing percentage had a higher feed conversion efficiency. However, in contrast to the present study, a stronger relationship was observed with the weight of lamb weaned per kg DM consumed increasing 28% when lambing percentage increased from 105% to 160%. This is similar to Harrison et al. (2014) who, using the GrassGro simulation model, reported that increasing ewe fecundity from 0.94 to 1.54 lambs per ewe increased the total product sold by 27% and resulted in a 10% reduction in breeding ewe flock numbers.

A caution with interpreting the impact of lambing percentage on feed conversion efficiency is that the results observed in this research were assumed to arise from a genetic basis for higher ovulation rates and conception rates. Therefore, these results cannot be extrapolated to situations where reproductive rate increases through better ewe nutrition because, in such cases, higher average dry matter intake by breeding ewes might also be expected.

Lamb Growth Rate

In contrast with Geenty (1995) and Large (1970), who both did not take a whole-of-system approach, this study has found that lamb liveweight gain had only a small impact on the overall efficiency of meat production, with pre-weaning liveweight gain only having a particularly small impact. This is similar to the results of Cruickshank et al. (2009) who, also using a whole-of-system approach, calculated that increasing lamb growth rate by 10% reduced production efficiency (CH_4/lamb) by just 2.0%. Although not intuitively obvious, there were many different reasons why lamb growth rate had a small impact on whole-of-system feed conversion efficiency.

First, in a flock situation, lamb energy demand for maintenance only made up a small proportion of total system energy requirements. For example, in the base model, although the maintenance energy[8] cost of sale lambs was 43% of total energy requirement for these lambs (1,271,454 MJME ÷ 2,948,582 MJME), it only comprised 13% of the total system feed requirement (1,271,454 MJME ÷ 10,000,000 MJME). Therefore, although faster lamb growth rates allowed earlier lamb slaughter dates and lowered the maintenance energy costs of lambs, because the proportion of total feed energy consumed by lambs was small, lamb growth rate therefore had a relatively unimportant impact on whole-of-system feed conversion efficiency. The implication of this is that if the maternal feed costs of the breeding ewe flock decreases (or the proportion of lamb energy demand increases), lamb liveweight gain would be expected to have a greater impact on feed conversion efficiency. Two ways how the relative feed costs of the breeding ewe flock can be decreased are through higher lambing percentage (of both ewes and hoggets) and higher target carcass weight. For example, if lambing percentage increased, assuming a fixed supply of feed energy, ewe numbers would reduce thus increasing the proportion of lamb energy requirements. Also, if target carcass weight was higher, increasing average growth rate would have a greater impact on reducing the time required to reach slaughter weights and would therefore have a greater impact on the maintenance energy costs of lambs. The effect of lamb growth rate under difference scenarios of ewe lambing percentage and target carcass weight are tested in Chapter 7.

Pre-weaning lamb growth rate also had a small impact on feed conversion efficiency due to the feed penalty associated with the double conversion of feed. For example, assuming it was hypothetically feasible for lambs to eat sufficient quantities of grass to meet their energy demands immediately from birth (and ewes were not required to produce milk), then the energy requirement of all sale lambs would be 1,001 MJME per lamb[9]. In comparison, if all the lambs are assumed to eat no grass during lactation, and all energy was supplied via milk, then the total energy requirement of sale lambs would be 1,258 MJME per lamb. Thus, during the lactation period, the double conversion of feed from grass to milk and then from milk to either lamb maintenance or lamb growth constitutes a 26% feed penalty compared to the post-weaning period when this does not occur. Therefore, this

[8] Including the additional energy cost of the ewe required to synthesis the milk used by the lamb for maintenance energy prior to weaning

[9] Assuming all other parameters were at baseline levels

supports the view of Wallace (1953) who suggested that the early weaning of lambs may be an important strategy for increased system feed conversion efficiency. In this study, it was assumed that weaning occurred 12 weeks after the date of lambing for MA ewes and 10 weeks after the date of lambing for hoggets. However, Litherland et al. (2007) reports that weaning is feasible from 8 weeks of age.

A third reason why lamb growth rate had only a small effect on whole-of-system feed conversion efficiency was because, in the base model, higher lamb growth rates actually had a negative feed conversion efficiency impact in relation to female replacement animals. This was because these animals reached higher liveweights at an earlier age and hence had higher maintenance requirements, but without any attributed benefits of enhanced reproductive performance. If higher hogget lambing were assigned to these animals then the benefits of higher lamb growth rates would have increased. Interactions between lamb growth rate and hogget lambing were feasible within the model and are investigated in Chapter 7. If it was assumed that increasing the pre-weaning liveweight gain of sale lambs did not impact on the liveweight gain of lambs kept as replacements (which remained at their baseline growth rate), feed conversion efficiency of the livestock system would have increased from 3.12 g carcass/MJME at 250 g/day to 3.18 g carcass/MJME at 450 g/day. This is a three-fold increase in the impact of pre-weaning growth rate on feed conversion efficiency in comparison to the baseline model.

A fourth reason for the low impact of pre-weaning lamb growth rate (especially when compared to the impact of post-weaning growth rate) was due to the fact that in the baseline model it was assumed that increased growth rate of lambs that survived also increased the growth rate of lambs the died during the lactation period. This meant that the efficiency gains of lower maintenance energy costs of lambs that were sold were partly offset by increased wastage of lambs that died (due to their increase in energy demand for growth and maintenance). For example, in the base model, 114 lambs (6.3% of lambs born) died during the lactation period and although these lambs were assumed to die half-way during lactation, the combined energy requirement of these lambs was 60,776 MJME or 0.6% of total system feed demand. When the pre-weaning liveweight gain of single MA ewe lambs increased to 450 g/day (and the liveweight gain on all other lambs, including lambs that died, were increased proportionately), the MJME requirement for lambs that died increased to 96,192 MJME (840 MJME per lamb) and 1.0% of total system feed demand. If the liveweight gain and energy requirements of lambs that died during the pre-weaning period was assumed to be fixed and was not influenced by the liveweight gain of sale lambs then increasing pre-weaning liveweight would have a 1.7 fold increase in the impact on feed conversion efficiency (from 3.13 g carcass/MJME at 250 g/day to 3.16 g carcass/MJME at 450 g/day).

The lower than expected effect of pre-weaning growth rate on feed conversion efficiency could also have been because, under the baseline assumptions, the sale of lambs "off-mother" prior to weaning did not impact on lamb dressing-out percentage. However even with possible changes in dressing-out percentage, when pre-weaning lamb growth rate was changed independently from other system parameters, this did not have any considerable impact on whole-of-system feed conversion efficiency. This has important implications in regards to the wisdom of using individual animal performance parameters as a guide to systems production output.

A further reason explaining the greater impact of post-weaning lamb growth rate on feed conversion efficiency was that, in this research, a lower absolute post-weaning lamb growth rate was tested in comparison to that of pre-weaning lamb growth rate. This is important in relation to the misleading nature of reporting percentage changes (Appendix A).

In comparison to pre-weaning lamb growth rate, the greater effect of post-weaning lamb growth rate on feed conversion efficiency can be explained by the fact that lambs were heavier in the post-weaning period. This meant that they had a higher maintenance energy cost which therefore increased the energy 'savings' of earlier slaughter. The other primary factor explaining why post-weaning lamb growth was more important than pre-weaning lamb growth rate was due to the time period. For example, to test this, the base model assumptions were modified so that 1.) the double-conversion effect was reversed, 2.) the growth rate of replacement lambs and lambs that died during the lactation period was de-linked from the growth rate of the input parameter, and 3.) analysis between pre-and post-weaning growth rate was made on an equal playing field by having both parameters ranging from 100 to 300g/day with the default parameter being 200g/day. However, even in this extreme scenario, increasing pre-weaning growth rate from 100g/day to 300g/day only increased feed conversion efficiency by 2.4% compared to an increase of 12% when the post-weaning growth rate parameter was increased. This was because, although increasing pre-weaning growth allowed for a decrease of 79 days on the average time to slaughter, post-weaning growth rate had a saving of 139 days. Post-weaning growth rate therefore has a greater impact on feed conversion efficiency because it has the greater potential impact on time to slaughter.

It is important to note that the fact that pre-weaning lamb growth rate did not have a large effect on system feed conversion efficiency does not mean that this parameter is unimportant. This is because pre-weaning growth has significant impacts on prices and costs of the farming enterprise, particularly through feed demand seasonality effects. The effect of pre-weaning lamb growth rate on economics is shown in Chapter 8.

Ewe Size

Consistent with the findings of Rutherford et al. (2003) and Curll et al. (1975), it was found that lower liveweight ewes increased feed conversion efficiency as a result of lower maintenance energy requirements per ewe. However, in contrast with these studies, change in ewe size had a smaller impact on overall feed conversion efficiency. For example while this study recorded a 4.5% increase in feed conversion efficiency for a 10 kg decrease in ewe liveweight (from 65 kg to 55 kg), Rutherford et al. (2003) reported a 13% increase in meat output per ha for a 10 kg decrease in ewe size. Also, from data from an on-farm experiment involving 360 Border Leicester × Merino ewes, Curll et al. (1975) reported that ewes that were 57 kg at mating would be able to produce between 0.08-0.10 kg lamb per kg DOM of feed intake depending on the post-mating nutritional treatment and assuming ewes were stocked such that total feed demand was 20,000 kg DOM. In contrast Curll et al. (1975) also reported that ewes that were 45 kg at mating (12 kg lighter) would be able to produce between 0.13-0.20 kg lamb per kg DOM of feed intake, which represents a 30% -150% increase in feed conversion efficiency compared to the heavier ewes. The discrepancy of magnitude in the effect of ewe size in relation to the results of this study are partly explained by the fact that both Rutherford et al. (2003) and Curll et al. (1975) do not calculate the contribution of mutton production of cull ewes to total meat output. Therefore they ignore the negative efficiency impact that smaller ewes have on mutton output and thus total meat sales and consequently overstate the biological efficiency of small ewes. The large efficiency impact of small ewes observed by Curll et al. (1975) is also due to variance in the seasonal liveweight as a consequence of nutrition. This contrasts to this study where it was assumed that changes to ewe size was a function of genetic parameters and the seasonal change in liveweight was assumed constant.

When interpreting the effect of ewe size on whole-of-system feed conversion efficiency, a factor to consider is the sensitivity of model results to the maintenance energy requirement of ewes and the standard reference weight of sale lambs. For example, in the process of model validation, increasing the assumed mature size or “standard reference weight” of lambs to 100 kg for ram lambs and 80 kg for ewe lambs resulted in a 1.7 fold increase in the relative improvement in feed conversion efficiency when ewe size was reduced from 80 kg to 50 kg.

In interpreting the results, it is also useful to remember that this research assumes that liveweight differences are determined genetically rather than a function of nutrition and thus assumed independent from other performance parameters. Consequently, in contrast to the observations of Cook (2007), Coop (1962), and Rutherford et al. (2003), changes in ewes size did not have negative impacts on either ewe reproductive performance or milk production and lamb growth rate. This assumption is feasible in that there are sheep breeds with low liveweight and high reproductive performance and high lamb growth, as well as sheep breeds with high liveweight but low ewe reproductive performance and low lamb growth rates (Geenty et al., 1985; Meadows, 2008; Morgan, Fogarty, Nielsen, & Gilmour, 2007; Peart, 1967). Nonetheless, to test the sensitivity of potential interdependencies between these variables, the effect of ewe size under different scenarios of reproductive performance and lamb growth rate and target carcass weight are investigated in Chapter 7.

Carcass Weight

Although there was a marginal decline in the increase in feed conversion efficiency with increasing lamb carcass weight, in contrast with Large (1970), even at very heavy carcass weights there was a positive relationship. There are two factors that may explain this. First, growth rate was assumed to be linear in the post-weaning period. When carcass weights are low or when lamb growth rates are high this is unlikely to result in significant error. However, linear growth rates are unlikely to represent reality under situations with low average growth or when carcass weight is very high (Owens et al., 1993). Second, in the base model, dressing-out percentage is linked to carcass weight. It was assumed that as carcass weight increases, dressing-out percentage also increased. However, if dressing-out percentage was fixed at baseline levels, increasing carcass weight from 12 kg to 24 kg would increase feed conversion efficiency by 24% rather than 28%. Consequently, although changes in dressing-out percentage impact on feed conversion efficiency, this was not a major factor driving the large increase in feed conversion efficiency as a result of changes in carcass weight.

Hogget Lambing

Maiden ewes represent a cohort of animals that are not fully contributing to enterprise productivity. Earlier mating of ewes as hoggets reduces the total amount of feed energy consumed by these animals before they contribute to reproduction of the flock. The results of this study are consistent with other studies including Cruickshank et al. (2008), Harrison et al. (2014) and Alcock et al. (2015). For example, using the GrassGro simulation model, Alcock et al. (2015) observed that reducing the maiden ewe mating age from 19 months of age to 7 months of age increased the total liveweight of stock sold (both lambs and cull ewes) by 8.3% from 303 kg Lwt/ha to 328 kg Lwt/ha for yearling lamb finishing systems in Australia.

Cull Age

With other production parameters kept fixed as per the baseline model, it was found that feed conversion efficiency decreased the longer ewes were kept beyond 6.3 years. This contrasts with Cruickshank et al. (2009) who reported that increasing ewe cull age from 5 to 6 years had one of the greatest impacts (4.6% reduction) on methane efficiency (kgCH_4/lamb). However, this difference in findings is due to the fact that the measure of efficiency used by Cruickshank et al. (2009) does not incorporate changes to the meat carcass output of cull ewes.

Similar to this study, a negative relationship between cull age and the biological efficiency of sheep production systems was also reported by Large (1976, p. 52) and is also consistent with studies on cattle systems (Taylor et al., 1985) and deer systems (Fennessy & Thompson, 1989). For example, Taylor et al. (1985) has recommended that all female progeny should be bred from and slaughtered at the minimum age that is consistent with maintaining the overall size of the breeding herd. This has been justified in that the later the dam is herself slaughtered the less efficient is the production of meat from these cull females. In comparison, if the dam is slaughtered at an early age then a considerable part of the conventional maternal overhead cost of producing a calf disappears by becoming part of productive growth.

However, in respect to economics, female longevity in livestock systems can still be important due to the price differential between mutton and lamb meat. For example, a younger flock age structure increases feed conversion efficiency as a higher total amount of meat can be sold. However, the proportion of mutton to lamb carcass is higher. Therefore, while a young cull age may have a positive effect on feed conversion efficiency, it may reduce profitability.

A reason why the loss in meat output from higher ewe deaths outweighed the energy savings of lower hogget numbers is because, in the baseline scenario, hoggets were mated, and while only a small number of lambs are born, this had the effect of decreasing the feed overhead cost of replacement animals per unit of output.

6.11.2 The Effect of System Parameters on the Seasonality of Feed demand

In this research, the livestock system had a very large effect on the seasonality of feed demand. This is in contrast with Woodford (1997), who found that alternative venison production systems did not have a very large impact on the seasonality of feed requirements. From the results, it is apparent that, in relation to matching feed supply and demand, by tailoring the sheep farming systems, system feed demand can be adjusted to match a wide range of environmental conditions.

In relation to increased lambing percentages, it can be argued that the seasonality impacts are not intuitively obvious. Increased lambing percentages resulted in more twins, and in the absence of complementary strategies relating to pre-weaning growth rates, then it was actually post-weaning where the overall system demand increased. This contrasts with the conclusions of Brookes et al. (1998) who found that increased feed demand for high lambing ewes occurred mainly from late pregnancy until weaning. The difference in findings is due to the modelling method used. For example, while the model used in the present study controlled ewe numbers so that total feed demand of the system remained constant, the model used by Brookes et al. (1998) kept the size of the ewe flock constant but adjusted the total feed energy demand of the system.

Assuming a fixed feed energy requirement, although lambing percentage increased post-weaning system feed demand, the size of this impact depended on the growth rate of lambs and on the weight at which lambs were slaughtered. For example, if lambs grew fast pre-weaning and/or were slaughtered at low carcass weights, then increased lambing percentage would have a much smaller impact on feed demand in the post-weaning period compared to if lambs grew slowly and/or lambs were killed at much heavier carcass weights. The effect of lambing percentage under different scenarios of lamb growth rate and target carcass weight is shown in Chapter 7.

In relation to carcass weight, the direction of shift in the seasonality of feed demand is intuitively obvious but the extent of the shift is remarkable. This has major implications for management of feed supply.

Lamb growth rate had a major impact on the seasonality of system feed demand. Accordingly, and depending on the availability and cost of pre-weaning versus post-weaning feed, and the price premiums for early production, then increasing lamb growth rates may still have a high impact on economic returns despite not having a large impact on feed conversion efficiency.

6.11.3 Stocking Rate

In order to keep system feed demand constant at 10,000,000 MJME, single-factor experimentation of system parameters forced ewe numbers at mating date to vary between 1,134 ewes and 1,507 ewes (Figure 6.17). This represents 33% change in ewe numbers. This compares to Cruickshank et al. (2009) who observed that production parameters such as scanning percentage, cull age, and hogget lambing had a large impact (21% reduction) on the number of ewes able to be carried. In relation to ewe size, in contrast with Rutherford et al. (2003), who reported that for the same amount of feed 14% more 60 kg ewes could be run in comparison to 70 kg ewes, in this study, 60 kg ewes resulted in an increase of just 6.7% in ewe numbers in comparison to 70 kg ewes (Table 6.4). In relation to ewe lambing percentage, the results observed in this research are consistent with that observed by Harrison et al. (2014).

From the results found in this study, a key insight is that unless attempts at increasing feed conversion efficiency through improvements to livestock production parameters are accompanied by changes in farm feed supply, the size of the ewe flock may need to increase or decrease by a considerable degree to compensate for the change in total feed demand. If this does not occur then the sensitivity of ewe numbers to changes in system parameters, especially to parameters such as lamb carcass weight, implies that considerable feed shortages may occur and overall production targets may not be achieved.

A second key insight from Figure 6.17 is that each of the livestock parameters tested in this research had quite large differences in respect to their impact on ewe numbers, both in terms of the magnitude of the impact and on the slope of the response curve. Implicit in this finding is that, by itself, stocking rate is an inadequate predictor of overall system feed conversion efficiency. For example, from the results of single factor experimentation presented in this chapter, feed conversion efficiency had an R^2 value of just 0.39 in relation to its correlation with the number of ewes at mating date. Therefore, the conclusions found in this study build on from those of Woodford and Nicol (2005) who argue that comparative analysis of livestock systems cannot be based on the number of animals carried per hectare of land but must include allowance for production variables. Notwithstanding, it is notable that extreme values of feed conversion efficiency correspond with extreme stocking rates and this issue is explored further in Chapter 7.

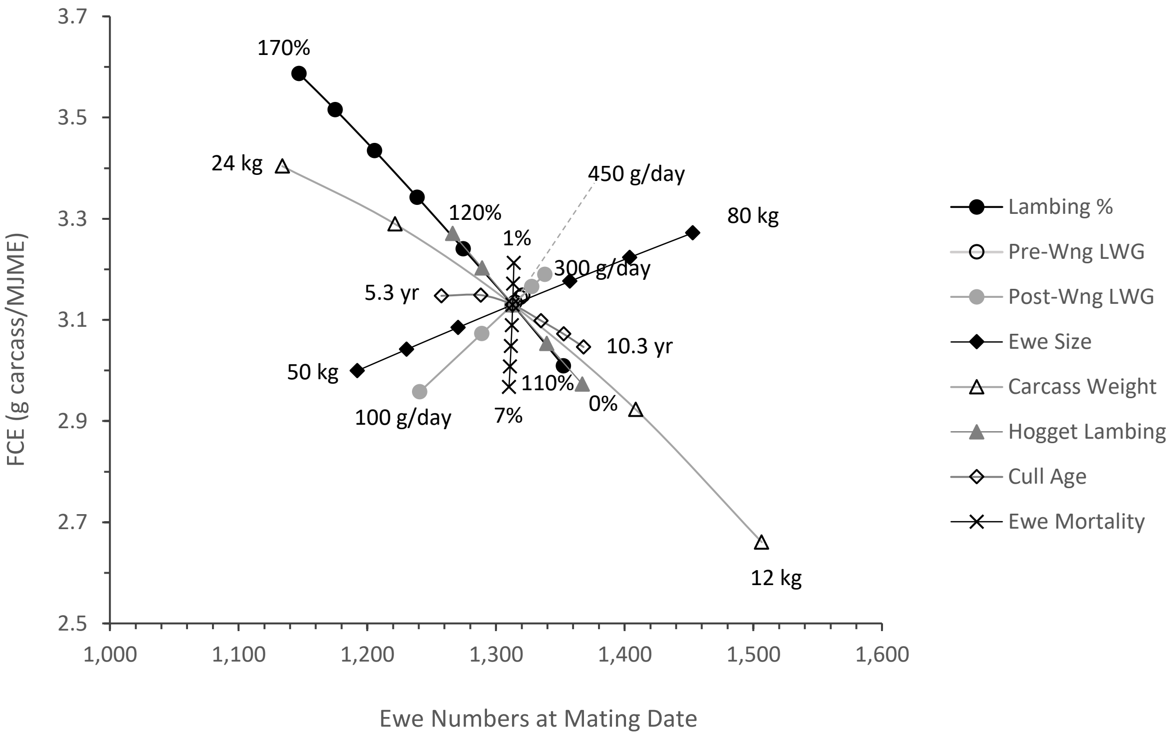


Figure 6.17 Relationship between feed conversion efficiency (g carcass/MJME) and ewe numbers at mating date

6.12 Summary of Key Findings

When key parameters of the livestock system were tested one-at-a-time with all other production parameters fixed as per baseline values, key findings are as follows:

1. Of the livestock parameters that were tested, lambing percentage, carcass weight, hogget lambing, and ewe size had the greatest impact on feed conversion efficiency. This was because these strategies had a large effect on production output in relation to per lamb maternal feed overhead costs.

2. Liveweight gain had only a small impact on the overall efficiency of meat production. This was because in a flock situation, lamb energy demands for maintenance, which on a per lamb basis decrease as growth rates increase (consequent to earlier slaughter date), only made up a small proportion of total system energy requirements. However, pre-weaning growth rates did have a major impact on the seasonality of total flock feed demands.

3. Within a fixed feed supply situation, ewe numbers were very sensitive to changes in lambing percentage and target carcass weight.

4. If farmers want to increase carcass weight by 1 kg from 18 kg to 19 kg, within a fixed total supply of feed, then it will increase overall carcass production 1.94%, but will reduce system feed demand 2.15% during pregnancy and 2.28% during lactation and increase feed demand 3.59% post-weaning. It will also require ewe numbers to reduce by 2.28%. If farmers wish to *retain existing* ewe numbers, then increasing carcass weight per lamb by 1 kg from 18 kg to 19 kg would result in whole-of-system feed demand increasing 0.1% during pregnancy, 0% during lactation, 6% during post-weaning, and 2.3% overall.

5. In general, improvements in feed conversion efficiency were not linear with a notable decline in the additional benefit for each additional increase in carcass weight, lambing percentage and post-weaning growth rate.

6. In relation to a fixed total supply of feed, the overall system benefits tend to be lower than is superficially apparent from consideration of system components. For example, whereas increasing carcass weight from 12 kg to 24 kg increased lamb output per ewe by 100%, the system improvement in meat production was only 28%. It is clear that major productivity improvements require a focus on multiple parameters of the system.

7. In relation to the seasonality of feed demand, the effect of improvements in system parameters were not always intuitively obvious. However, they were explainable. For

example, increased lambing percentages increased the number of twins, and in the absence of complementarity strategies relating to pre-weaning growth rates, then it was actually post-weaning where the overall system demand increased. In relation to carcass weight, the direction of shift in the seasonality of demands was intuitively obvious, but the extent of the shift was remarkable. This has major implications for management of feed supply.

Chapter 7

Multi Factor Experiments

7.1 Introduction

The number of permutations or possible combinations in which scenarios of lambing percentage, pre-weaning and post-weaning lamb growth rate, ewe size, carcass weight, hogget lambing, cull age and death rate can be combined is vast. For example, in Chapter 6, seven scenarios of lambing percentage, five pre-weaning lamb growth rates, five post-weaning lamb growth rates, and seven ewe sizes were tested. Also, five carcass weights, five scenarios of hogget lambing, six cull ages and seven scenarios of ewe mortality were tested. This alone gives **1,286,250** possible ways in which the sheep livestock system can be configured.

In this chapter, the effect of simultaneous changes in livestock parameters on whole-of-system feed conversion efficiency (g carcass/MJME) and feed demand seasonality are explored. The purpose is to investigate interrelationships between components of the livestock system. However, due to the impracticalities of testing every combination of livestock parameters, only a limited number of different combinations are tested. Investigations are focused on testing the combined effect of related parameters and are based on a number of questions that arose from Chapter 6 when parameters were tested one-at-a-time.

First, the effect of simultaneously changing all livestock parameters from their minimum to maximum values was tested. Second, the effect of increased lambing percentage was tested under a range of different lamb carcass weights. Next, the combined effect of pre-weaning and post-weaning growth rate was tested. Fourth, the effect of increased carcass weight was tested for different pre-weaning and post-weaning lamb growth scenarios. Lamb growth rate was then tested under changed baseline assumptions for ewe and hogget lambing percentage. Last, a range of ewe size scenarios were tested.

7.2 Minimum and Maximum Scenarios

In relation to their individual impact on feed conversion efficiency, minimum and maximum values for input parameters are shown in Table 7.1. When these parameters were tested simultaneously, increasing all parameters from their minimum to maximum values increased feed conversion efficiency by 117% (Table 7.1). It is worth highlighting here that, in these experiments, minimum and maximum values for system scenarios relate to parameter values where feed conversion efficiency was found to be lowest and highest in single-factor experiments and therefore do not relate to the absolute minimum or maximum values for system parameters. For example, ewe size had an inverse relationship with feed conversion efficiency (Section 6.5) and therefore, for this parameter, the maximum absolute value was used for the minimum scenario, and the minimum absolute value was used for the maximum scenario.

Table 7.1 Input values for livestock parameters and model results for minimum, baseline and maximum scenarios of the sheep livestock system

	Minimum Values	Baseline Values	Maximum Values
Input Parameters			
Average lambs tailed per ewe (%)*	110%	120%	170%
Ewe size (kg)	80	65	50
Pre-weaning growth rate (g/day)	250	300	450
Post-weaning growth rate (g/day)	100	200	300
Lambs tailed per hogget (%)	0%	30%	120%
Carcass weight (kg)	12	18	24
Cull age (years)	10.3	7.3	6.3
Ewe mortality (%)	7%	3%	1%
Model Outputs			
FCE (g carcass/MJME)	1.96	3.13	4.24
Lamb carcass: total carcass (%)	71%	78%	89%
Ewe numbers	1,429	1,313	997
Hogget numbers	258	272	229
MJME pregnancy	35.1%	29.0%	19.2%
MJME lactation	31.0%	32.7%	41.4%
MJME post-weaning	33.9%	38.2%	39.4%

*When flock structure is at baseline levels.

Despite ewes being smaller, in the maximum model there were also 433 (or 30%) less ewes in comparison to the minimum model. This reduction in ewe numbers was due to the higher energy requirement per lamb (due to faster growth rates and higher carcass weights), higher energy costs per hogget (as a result of the higher hogget mating percentage) and due to the higher reproductive performance of ewes. The maximum model also had a much higher proportion of lamb carcass production with the proportion of lamb carcass to total carcass increasing from 71% to 89% when system parameters where changed from their minimum to maximum values.

In comparison to the minimum model, the maximum model also had 45% lower feed demand during pregnancy, 33% higher feed demand during the lactation period and 16% higher feed demand in the post-weaning period (Figure 7.1). This demonstrates that high performance livestock systems tend to have much lower energy demand over ewe pregnancy (i.e. lower feed overheads), followed by very high energy demands in the lactation and early post-weaning periods. In contrast, livestock systems with lower feed conversion efficiency tend to have flatter energy profiles with much higher energy demands over winter.

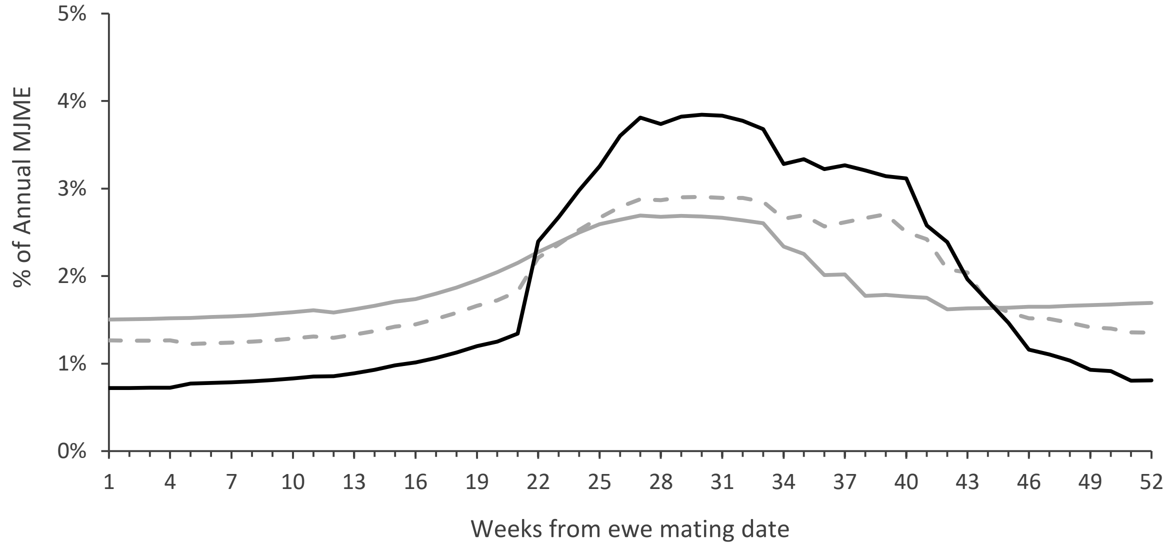


Figure 7.1 The effect of minimum and maximum livestock scenarios (——min, – – –baseline, —— max) on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date

A cautionary note when interpreting the above results is that it has been assumed here that the simultaneous changes in system parameters were feasible. This may not necessarily be the case, especially if aiming to decrease ewe size while at the same time aiming to increase carcass weight, lambing percentage and lamb growth parameters. This issue is discussed further in following sections where the effect of ewe size (or other parameters) are tested under a range of different scenarios.

7.3 The Combined Effect of Lambing Percentage and Lamb Carcass Weight

When both lambing percentage and lamb carcass weight were simultaneously increased from 110% to 170% and from 12 kg to 24 kg, there was a very large change in feed conversion efficiency (Table 7.2). However, there were minimal systems interactions between lambing percentage and carcass weight parameters which meant that the increase in feed conversion efficiency was approximately additive. For example, the summed feed conversion efficiency impact of the individual components of 28.7% for carcass weight and 20.8% for lambing percentage as shown in Table 7.2 was 49.5% which was very close to the overall 49.9% change in feed conversion efficiency when parameters were changed in-combination.

Table 7.2 The combined effect ewe lambing percentage (lambs tailed per ewe mated) and lamb carcass weight (kg) on whole-of-system feed conversion efficiency (g carcass/MJME)

Carcass Weight (kg)	Lambing %							Change % from 110-170%
	110%	120%	130%	140%	150%	160%	170%	
12	2.55	2.66	2.76	2.85	2.94	3.02	3.09	**20.8%**
18	3.01	3.13	3.24	3.34	3.43	3.52	3.59	**19.2%**
24	3.29	3.40	3.51	3.61	3.69	3.76	3.83	**16.5%**
Change % from 12-24 kg	**28.7%**	**27.9%**	**27.1%**	**26.3%**	**25.5%**	**24.8%**	**24.0%**	**49.9%**

At low carcass weight, the number of lambs tailed per ewe had a large impact on feed demand in the weeks immediately following weaning (Figure 7.2). However, as carcass weight increased, increased lambing percentage increased feed demand further back in the season and also increased feed demand in the early part of the pregnancy period. What is evident is that, assuming other parameters remain constant, and within a fixed feed demand constraint, while both ewe lambing percentage and lamb carcass weight were two of the most important drivers of biological efficiency, it was increased lamb carcass weight rather than increased lambing rates which resulted in a fundamental shift in the profile of feed demand.

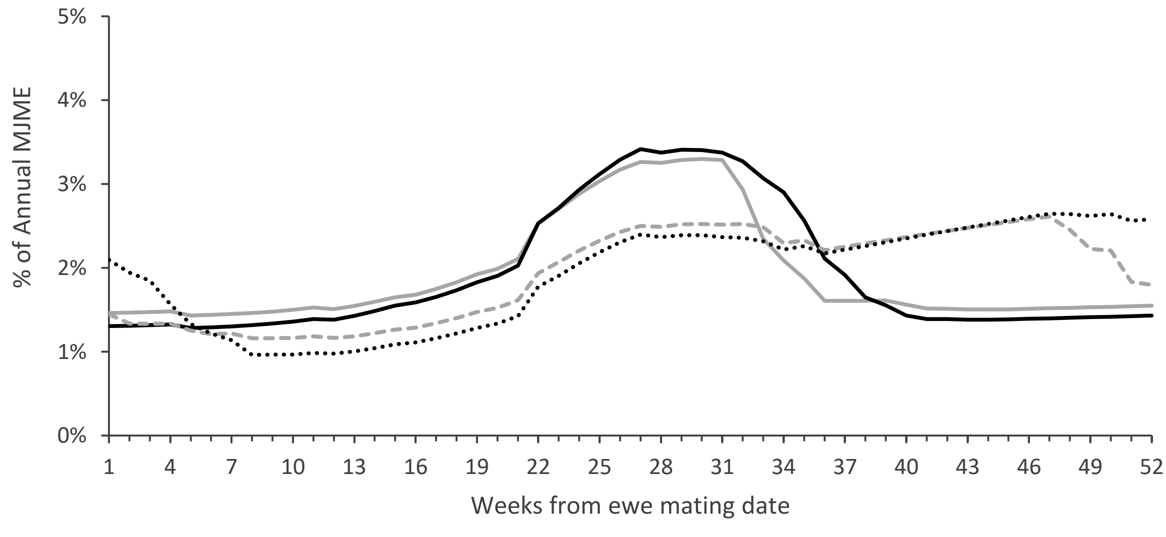


Figure 7.2 The effect of light (12 kg) and heavy (24 kg) carcass weight and low (110% lambs tailed per ewe mated) and high (170% lambs tailed per ewe mated) lambing percentage on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date (——— light low, ——— light high, – – – heavy low, ……… heavy high)

7.4 The Combined Effect of Pre-Weaning and Post-Weaning Lamb Growth Rate

There were strong negative systems interactions between pre-weaning and post-weaning lamb growth rate parameters and whole-of-system feed conversion efficiency (Table 7.3). For example, the overall combined feed conversion efficiency impact of increasing pre-weaning growth rate of MA ewe single lambs from 250 g/day to 450 g/day and increasing post-weaning lamb growth rate of MA ewe single sale lambs from 100 g/day to 300 g/day was only half the added effect of the individual system components; i.e. the summed feed conversion efficiency impact of the individual components of 6.8% for pre-weaning lamb growth rate and 9.9% for post-weaning lamb growth rate as shown in Table 7.3 was 16.7% compared to the overall 8.4% change in feed conversion efficiency when parameters were changed in-combination. Also, when the post-weaning growth rate of MA ewe single sale lambs was 300 g/day, increasing the pre-weaning growth rate of MA ewe single lambs from 250 g/day to 450 g/day actually reduced feed conversion efficiency by 1.4%.

Table 7.3 The combined effect of pre- and post- weaning lamb liveweight gain (g/day) on whole-of-system feed conversion efficiency (g carcass/MJME)

Post-Weaning LWG (g/day)	Pre-Weaning LWG (g/day)					Change % from 250-450 g/day
	250	300	350	400	450	
100	2.91	2.96	3.01	3.07	3.11	**6.8%**
200	3.13	3.13	3.13	3.14	3.15	**0.6%**
300	3.20	3.19	3.18	3.17	3.16	**-1.4%**
Change % from 100-300 g/day	**9.9%**	**7.8%**	**5.5%**	**3.1%**	**1.4%**	**8.4%**

There are four reasons that explain these counter-intuitive results. First, as pre-weaning growth rate increased, the weaning weight of lambs were higher which, under the baseline assumption that target carcass weight was constant, resulted in a smaller differential between weaning weight and target slaughter weight. Consequently, increased post-weaning growth rates had a diminished ability to influence the average date of slaughter and therefore did not result in a large saving in maintenance energy requirement for lambs. Accordingly, as pre-weaning growth rate increased, the impact of post-weaning growth rate on feed conversion efficiency decreased.

The second reason for the negative systems interaction between pre-weaning and post-weaning lamb growth rate was due to the influence of the timing of lamb growth on lamb maintenance energy requirements, especially in relation to replacement lambs. This is best explained through the use of a simple thought experiment[10]. For example, consider a replacement ewe lamb able to remain at its birthweight for the duration of lactation (e.g. having a pre-weaning growth rate of zero) and then just prior to mating date as a hogget having an infinite growth rate such that at that date it is able to reach the target weight without any detrimental impact on reproductive performance. Remembering that maintenance energy requirement is a function of liveweight, this scenario would require very little energy for lamb maintenance and would be considerably more energy efficient in comparison to the reverse scenario of a replacement ewe lamb having an infinite growth rate at the date of birth such that it reached target mating weight on that same date and then remained at this liveweight until hogget mating date.

As this thought experiment illustrates, it is more efficient for replacement lambs to remain as small as possible for as long as possible. Therefore, when pre-weaning growth rate was increased, although feed conversion efficiency was positively influenced by the early sale of sale lambs (thus reducing lamb maintenance energy requirements) feed conversion efficiency was also negatively impacted by the fact that lambs were at higher liveweights at earlier ages which considerably increased the post-weaning maintenance energy requirement of replacement lambs. The balance of these two factors depends on the post-weaning lamb growth rate. For example, when post-weaning lamb growth rate was low, pre-weaning lamb growth had a large impact on the average time to slaughter and therefore, in this scenario, the energy saving from earlier sale of lambs outweighed the negative feed conversion efficiency impact of higher maintenance energy cost of replacement lambs. However, when post-weaning growth was high, pre-weaning growth rate had a much reduced impact on the change in average time to slaughter. This meant that, in this scenario, the negative feed conversion efficiency impact of higher maintenance energy costs of replacement lambs outweighed the benefit of reduced energy costs associated with an earlier lamb sale date.

The third reason that explained the negative systems interactions between pre-weaning and post-weaning lamb growth rate and feed conversion efficiency was the small differential between the energy requirements for liveweight gain during the pre-weaning period as compared to the energy required for liveweight gain post-weaning. This was due to the double conversion of energy during the lactation period, from pasture to milk and then from milk to lamb growth.

The last reason that explained the negative systems interactions between pre-weaning and post-weaning lamb growth rate and feed conversion efficiency was a result of the baseline assumption that, following weaning, lambs selected for replacements were not impacted by changes in the post-weaning growth parameter. Rather, the post-weaning growth rate of replacement lambs was a

[10] This is a concept that was often used by Einstein and other theoretical scientists and is based on the idea of using extreme imaginary examples to test ideas.

function of their weaning weight relative to their expected target weight at hogget mating date. This meant that increased post-weaning lamb growth of sale lambs was not associated with an increase in the energy required for maintenance for replacement lambs. This contrasts with the pre-weaning period where the growth rate of all lambs was assumed to be the same irrespective of whether these lambs were sold or are kept as replacements.

In relation to the seasonality of feed demand, pre-weaning lamb growth also had a considerable impact on the effect of higher post-weaning lamb growth rate. For example, when pre-weaning growth rate was only 250 g/day, increasing post-weaning growth rate from 100 g/day to 300 g/day reduced the total feed demand during pregnancy and increased feed demand 9.7% during lactation. Also, while feed demand increased considerably in the first half of the post-weaning period and then reduced considerably, overall feed demand increased by 1.2% (Figure 7.3). However, when pre-weaning lamb growth was 450 g/day, increasing post-weaning growth rate from 100 g/day to 300 g/day had minimal impact on feed demand.

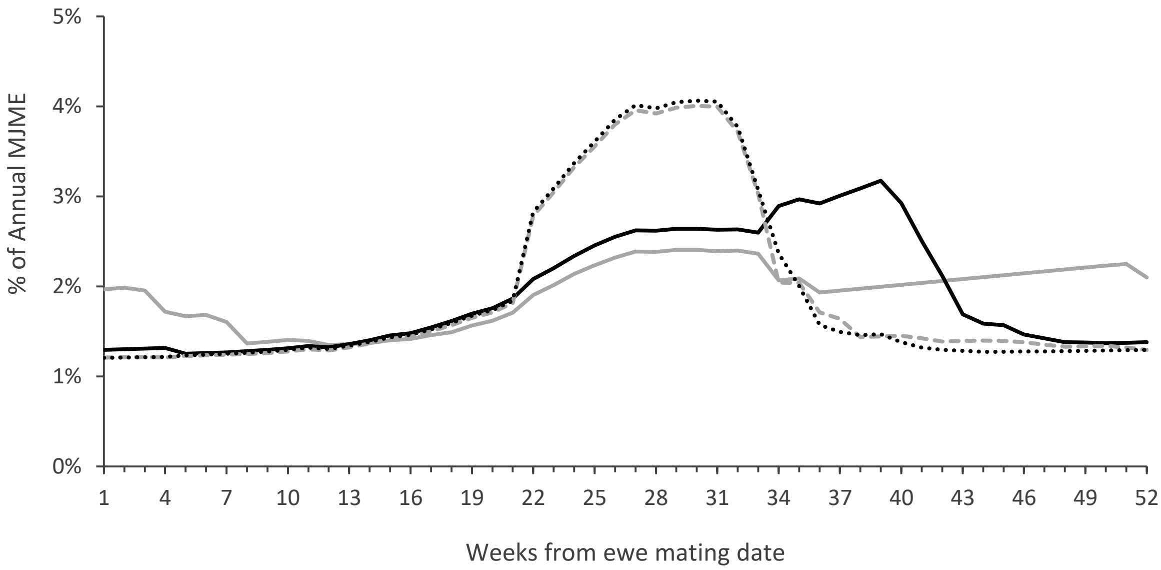


Figure 7.3 The effect of slow (250 g/day) and fast (450 g/day) pre-weaning and slow (100 g/day) and fast (300 g/day) post-weaning lamb growth rates on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date (—— slow slow, —— slow fast, – – – fast slow, ········· fast fast)

7.5 The Combined Effect of Carcass Weight and Lamb Growth Rate

The combined effect of carcass weight and lamb growth rate on both feed conversion efficiency and the seasonality of feed demand was first tested by simultaneously increasing carcass weight and pre-weaning lamb growth rate while keeping post-weaning growth rate at baseline levels. With pre-weaning lamb growth rate set at the baseline, simultaneous changes to both carcass weight and post-weaning lamb growth rate was then tested. Last, the effect of increasing lamb carcass weight was tested under low and high lamb growth scenarios for pre- and post-weaning lamb growth rate. In the low scenario, the pre-weaning lamb growth rate was set at 250 g/day and post-weaning lamb growth rate was set at 100 g/day. In the high lamb growth scenario, the pre-weaning lamb growth rate was set at 450 g/day while the post-weaning lamb growth rate was set at 300 g/day.

The effect of pre-weaning lamb growth rate

With all other parameters set at baseline levels, pre-weaning growth rate did not have a very large impact on the effect between carcass weight and feed conversion efficiency (Table 7.4.). However, pre-weaning liveweight gain did have a considerable impact on the effect of carcass weight on the seasonality of feed demand. For example, at 12 kg carcass weight, increasing pre-weaning lamb growth rate from 250 g/day to 450 g/day had no change in feed demand in the ewe pregnancy period, but increased feed demand 13.1% in ewe lactation and reduced feed demand 13.4% in the post-weaning period. However, at 24 kg, increasing pre-weaning lamb growth rate from 250 g/day to 450 g/day reduced feed demand in ewe pregnancy by 14.3%, increased feed demand in ewe lactation by 52.9% and reduced feed demand in the post-weaning period by 20.3%.

Table 7.4 The combined effect of pre-weaning lamb liveweight gain (g/day) and lamb carcass weight (kg) on whole-of-system feed conversion efficiency (g carcass/MJME)

LWG (g/day)	Carcass Weight (kg)					Change % from 12-24 kg
	12	15	18	21	24	
250	2.66	2.92	3.13	3.29	3.40	**28.0%**
350	2.66	2.93	3.13	3.29	3.41	**28.0%**
450	2.67	2.93	3.15	3.32	3.43	**28.3%**
Change % from 250-450 g/day	**0.6%**	**0.4%**	**0.6%**	**0.9%**	**0.8%**	**29.1%**

The effect of post-weaning lamb growth rate

Post-weaning growth rate did have a measureable impact on the effect between lamb carcass weight and feed conversion efficiency (Table 7.5). Post-weaning growth rate also had a considerable impact on the effect between carcass weight and the seasonality of feed demand. At 12 kg carcass weight, increasing post-weaning lamb growth rate from 100 g/day to 300 g/day had almost no impact on overall feed demand in the pregnancy, lactation and post-weaning periods. However, at 24 kg, increasing pre-weaning lamb growth rate from 100 g/day to 300 g/day reduced feed demand in the ewe pregnancy period by 33%, increased feed demand in ewe lactation by 10% and increased feed demand in the post-weaning period by 29%.

Table 7.5 The combined effect of post-weaning lamb liveweight gain (g/day) and lamb carcass weight (kg) on whole-of-system feed conversion efficiency (g carcass/MJME)

LWG (g/day)	Carcass Weight (kg)					Change % from 12-24 kg
	12	15	18	21	24	
100	2.64	2.84	2.96	3.02	3.05	**15.4%**
200	2.66	2.92	3.13	3.29	3.40	**27.9%**
300	2.66	2.95	3.19	3.38	3.54	**32.8%**
Change % from 100-300 g/day	**0.7%**	**3.8%**	**7.8%**	**11.9%**	**15.9%**	**33.7%**

The effect of slow and fast pre- and post-weaning lamb growth rate scenarios

When pre-weaning and post-weaning lamb growth rates were changed simultaneously, the effect of carcass weight on feed conversion efficiency and the seasonality of feed demand was greater than when parameters were tested one-at-a-time. Overall, there were considerable systems interactions with the effect of lamb growth and carcass weight on feed conversion efficiency being multiplicative (Table 7.6).

Table 7.6 The effect of pre-weaning and post-weaning lamb liveweight gain (LWG) and carcass weight scenarios on whole-of-system feed conversion efficiency (g carcass/MJME)

Pre- and Post-Weaning LWG Scenario	Carcass Weight (kg)					Change % from 12-24 kg
	12	15	18	21	24	
Slow	2.61	2.80	2.91	2.98	3.02	**15.4%**
Baseline	2.66	2.92	3.13	3.29	3.40	**27.9%**
Fast	2.67	2.93	3.16	3.35	3.51	**31.1%**
Change % from Slow to Fast	**2.4%**	**4.9%**	**8.4%**	**12.4%**	**16.3%**	**34.2%**

In relation to the seasonality of feed demand, at heavier carcass weights, the high pre-weaning and post-weaning lamb growth scenario had a much greater impact on feed demands in the ewe lactation period. This was because at higher target carcass weights, slow lamb growth rates had the effect of increasing the number of lambs that were still on-farm at ewe mating date. This is graphically shown in Figure 7.4. At heavy carcass weights and slow growth rates, the profile of whole-of-system feed demand remains approximately the same throughout the year. As carcass weights decreased and lamb growth rates increased, the difference between the minimum and maximum weekly feed demand increased. This suggests that when feed supply is very seasonal, livestock systems with lower carcass weights and faster lamb growth rates may be required if feed supply and demand are to be closely aligned.

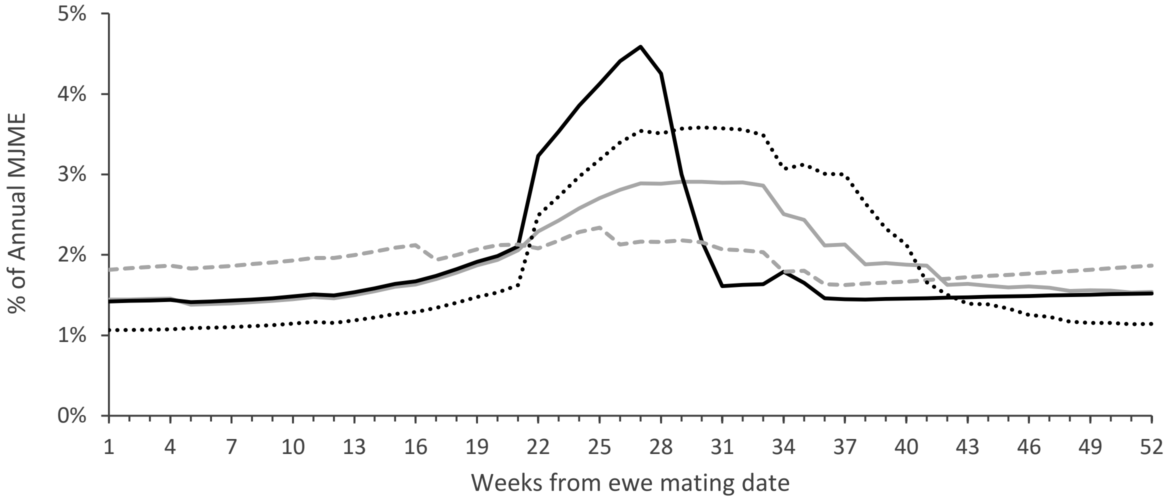


Figure 7.4 The effect of light (12 kg) and heavy (24 kg) carcass weight and slow (250 g/day pre-weaning and 100 g/day post-weaning) and fast (450 g/day pre-weaning and 300 g/day post-weaning) lamb growth rate on whole-of-system feed demand seasonality, measured as the percentage of annual total feed demand (MJME) that is required each week starting from ewe mating date (—— light slow, —— light fast, – – – heavy slow, ········· heavy fast)

7.6 Hogget Lambing Scenarios

While the decision to mate hoggets is independent from the reproductive performance of breeding ewes, there is a possible connection between the reproductive rate of hoggets and the reproductive rate of ewes. For example, when replacement hoggets are sourced from the ewe flock, genetic selection for high reproductive performance is likely to influence the potential lambing percentages of both hoggets and ewes in the long term. Pre-weaning lamb growth rate may also be correlated to hogget lambing (lambs tailed per total hogget) due to advantages associated with reaching higher liveweights before mating (Kenyon, 2012, p. 9). In the following experiments, the effect of hogget lambing on both feed conversion efficiency and the seasonality of feed demand was tested under changed baseline assumptions for ewe lambing percentage (lambs tailed per ewe mated) and pre-weaning lamb growth rate.

The effect of ewe lambing percentage

Increasing ewe lambing percentage from 110% to 170% and, in-combination, increasing hogget lambing from 0% to 120% increased feed conversion efficiency by 30.1%. This efficiency gain was less than the summed values for each parameter when considered by itself (Table 7.7). The reason for this was because, assuming a fixed feed energy constraint and variable animal numbers, higher ewe lambing percentage required a reduction in ewe numbers which consequently reduced the number of replacement hoggets needed. This therefore reduced the overhead feed costs of replacement hoggets which subsequently reduced the potential efficiency savings from higher hogget lambing.

Table 7.7 The combined effect of ewe lambing percentage (lambs born per ewe mated) and hogget lambing (lambs born per total hogget) on whole-of-system feed conversion efficiency (g carcass/MJME)

Hogget Lambing	Ewe Lambing				Change % from 110-170%
	110%	130%	150%	170%	
0%	2.84	3.09	3.30	3.47	**22.0%**
60%	3.01	3.24	3.43	3.59	**19.2%**
120%	3.16	3.37	3.55	3.70	**17.0%**
Change % from 0-120%	**11.1%**	**9.1%**	**7.6%**	**6.6%**	**30.1%**

Irrespective of ewe lambing percentage, hogget lambing did not have any sizeable impact on the seasonal profile of feed demand. Notwithstanding, hogget lambing had a smaller impact on seasonal feed demand when ewe lambing percentage was higher. Again, this was due to the fact that higher lambing percentages resulted in lower ewe and hogget numbers which reduced the overall impact of changes in the feed demand of hoggets and their progeny. As an example, when ewe lambing percentage was 110%, increasing hogget lambing from 0% to 120% reduced feed demand 5.2% during pregnancy and 2.1% during lactation but increased feed demand 6.1% post-weaning. When ewe lambing percentage was 170%, increasing hogget lambing from 0% to 120% reduced feed demand 4.1% during pregnancy and 1.6% during lactation, but increased feed demand 3.9% post-weaning.

The effect of pre-weaning lamb growth rate

Assuming post-weaning growth rates remained at baseline levels (200 g/day for single lambs), pre-weaning growth rate had only a small effect on feed conversion efficiency irrespective of the number of lambs born per hogget (Table 7.8). However, hogget lambing and pre-weaning lamb liveweight gain parameters were complementary with higher hogget lambing and pre-weaning lamb growth rate being slightly more than additive in their combined effect on whole-of-system feed conversion efficiency.

In relation to the seasonal profile of feed demand, as pre-weaning lamb growth rate increased, hogget lambing had a greater, albeit small, impact on whole-of-system feed demand during the pregnancy and post-weaning periods and a smaller impact on feed demand during the lactation period. For example, when pre-weaning lamb growth rate was 250 g/day, increasing hogget lambing from 0% to 120% reduced feed demand 3.8% during pregnancy and 2.4% during lactation, but increased feed demand 4.5% post-weaning. However, when pre-weaning lamb growth rate was 450 g/day, increasing hogget lambing from 0% to 120% reduced feed demand 5.9% during pregnancy and 0.5% during lactation, but increased feed demand 7.5% post-weaning.

Table 7.8 The combined effect of pre-weaning lamb liveweight gain (g/day) and hogget lambing (lambs born per total hogget) on whole-of-system feed conversion efficiency (g carcass/MJME)

Hogget Lambing	LWG (g/day)					Change % from 250-450 g/day
	250	**300**	**350**	**400**	**450**	
0%	2.97	2.97	2.98	2.98	2.98	**0.4%**
60%	3.13	3.13	3.13	3.14	3.15	**0.6%**
120%	3.27	3.27	3.28	3.29	3.29	**0.7%**
Change % from 0-120%	**10.0%**	**10.0%**	**10.1%**	**10.2%**	**10.3%**	**10.7%**

7.7 Ewe Size Scenarios

In Chapter 6, the effect of ewe size on feed conversion efficiency was tested assuming that changes to ewe size did not impact on either reproductive performance or lamb growth rate or achievable lamb carcass weight. This assumption contrasts with observations by Cook (2007), Coop (1962) Rutherford et al. (2003), and Meadows (2008) who note that ewe liveweight is strongly correlated to productivity. While bigger ewes may have higher animal performance levels as a consequence of increased nutrition, higher animal performance can also be a result of genetic correlations between ewe size and the genetic potential for ovulation rate and or milk yield and lamb growth rate (Geenty et al., 1985; Peart, 1967; Thompson & Thompson, 1953). For example, East Friesian ewes have higher milk production and their lambs have faster lamb growth rates in comparison to other breeds with lower liveweights (Morgan et al., 2007). In the following experiments, the effect of ewe size on feed conversion efficiency and the seasonality of feed demand was tested while simultaneously changing baseline assumptions for lambing percentage, pre-weaning lamb growth rate, and carcass weight parameters.

The effect of Lambing percentage

With other parameters at baseline levels, higher ewe lambing percentage reduced the potential efficiency savings associated with lower ewe size (Table 7.9). This was because, assuming a fixed feed energy supply and variable animal numbers, higher reproductive rates were associated with lower animal numbers and a lower total maternal overhead feed cost.

In relation to the seasonality of feed demand, as lambing percentage increased, lower ewe sizes resulted in lower feed demands in the pregnancy period and higher feed demands in lactation and post-weaning. For example, when lambing percentage was 110%, reducing ewe size from 80 kg to 50 kg reduced feed demand 13% during pregnancy, increased feed demand 14% during lactation but reduced feed demand 1% post-weaning. However, when lambing percentage was 170%, reducing ewe size from 80 kg to 50 kg reduced feed demand 16% during pregnancy, increased feed demand 11% during lactation and increased feed demand 2.8% post-weaning.

Table 7.9 The combined effect of ewe lambing percentage (lambs born per ewe mated) and ewe size (kg) on whole-of-system feed conversion efficiency (g carcass/MJME)

Ewe Lambing %	Ewe Size (kg) 50	60	70	80	Change % from 50-80 kg
110%	3.15	3.05	2.97	2.88	**-8.5%**
130%	3.38	3.29	3.20	3.11	**-8.1%**
150%	3.57	3.48	3.39	3.30	**-7.6%**
170%	3.71	3.63	3.54	3.45	**-7.0%**
Change % from 110-170%	**17.9%**	**18.9%**	**19.4%**	**19.8%**	9.6%

The effect of Pre-Weaning Lamb Growth Rate

Pre-weaning growth rate did not have a large effect on the relationship between ewe size and feed conversion efficiency (Table 7.10). However, ewe size did have a large influence on the effect of pre-weaning lamb growth rate on the seasonality of feed demands. When ewe size was 50 kg, increasing pre-weaning growth rate from 250 g/day to 450 g/day decreased overall feed demand during ewe pregnancy by 1.1%, increased feed demand during lactation by 57.2%, and decreased feed demand during the post-weaning period by 41.3%. In contrast, when ewe size was 80 kg, increasing pre-weaning growth rate had minimal effect on the overall feed demand during ewe pregnancy, increased feed demand during lactation by 41.8%, and decreased feed demand during the post-weaning period by 28.6%.

Table 7.10 The combined effect of pre-weaning lamb liveweight gain (g/day) and ewe size (kg) on whole-of-system feed conversion efficiency (g carcass/MJME)

LWG (g/day)	Ewe Size (kg) 50	60	70	80	Change % from 50-80 kg
250	3.27	3.18	3.08	3.00	**-8.5%**
350	3.27	3.18	3.09	3.01	**-8.2%**
450	3.29	3.19	3.10	3.02	**-8.1%**
Change % from 250-450 g/day	**0.4%**	**0.6%**	**0.7%**	**0.8%**	-7.7%

The effect of Carcass Weight

As target carcass weight was increased, ewe size had a smaller effect on feed conversion efficiency (Table 7.11). However, carcass weight had a large impact on the relationship between ewe size and seasonality of feed demand. When carcass weight was 12 kg, reducing ewe size for 80 kg to 50 kg reduced feed demand during the pregnancy period by 8.6%, increased feed demand during the lactation period by 19.1% and reduced feed demand in the post-weaning period by 11.1%. When carcass weight was 24 kg, reducing ewe size for 80 kg to 50 kg reduced feed demand during the pregnancy period by 14.7%, increased feed demand during the lactation period by 8.8% and increased feed demand in the post-weaning period by 4.1%.

Table 7.11 The combined effect of pre-weaning lamb liveweight gain (g/day) and ewe size (kg) on whole-of-system feed conversion efficiency (g carcass/MJME)

Carcass Weight (kg)	Ewe Size (kg)				Change % from 50-80 kg
	50	60	70	80	
12	2.81	2.71	2.62	2.54	**-9.8%**
16	3.15	3.05	2.95	2.87	**-9.0%**
20	3.37	3.28	3.20	3.12	**-7.7%**
24	3.52	3.44	3.37	3.29	**-6.5%**
Change % from 12-24 kg	**25.2%**	**27.1%**	**28.7%**	**29.8%**	**17.1%**

The combined effect of lambing percentage, lamb growth rate, and carcass weight

To determine the combined effect of lambing percentage, pre-weaning lamb growth rate and lamb carcass weight on the relationship between ewe size and feed conversion efficiency and the seasonality of feed demand, two different scenarios were tested. In the “low slow light” scenario, lambing percentage was set at 110%, pre-weaning lamb growth rate was 250 g/day and carcass weight was 12 kg. In the “high fast heavy” scenario, lambing percentage was 170%, pre-weaning lamb growth rate was 450 g/day and carcass weight was 24 kg.

Overall, ewe size had a much greater importance for feed conversion efficiency under the lower performance scenario (Table 7.12). Also the large variance in feed conversion efficiency between the low and high performance scenarios suggests that while small ewes would increase system feed conversion efficiency due to their lower energy requirement, if smaller ewes also result in major decreases in per head animal performance, then overall system efficiency would decrease.

Table 7.12 The effect of lambing percentage, pre-weaning lamb liveweight gain, carcass weight and ewe size scenarios on whole-of-system feed conversion efficiency (g carcass/MJME)

Lambing%, growth rate and carcass weight scenario	Ewe Size (kg) 50	60	80	Change % from 50-80 kg
Low Slow Light (LSL)	2.70	2.55	2.44	**-9.7%**
High Fast Heavy (HFH)	3.94	3.86	3.77	**-4.3%**
Change % from LSL to HFH	**46.1%**	**51.4%**	**54.8%**	**39.8%**

7.8 Validation of Model Results

Key validation issues in respect to this chapter are the potential interdependencies of system parameters and the feasibility of simultaneous changes to these parameters. Consequently, the additional validation required is this chapter over and above that required in Chapter 6 relates solely to the interactions, and the ability to logically explain the interactions observed in the results. As this has been done when presenting the results earlier in this chapter, it will not be repeated here. However, it is concluded that model results are 'explainable' and as such are valid for the purposes of comparing relative system efficiencies between system scenarios.

7.9 Discussion

7.9.1 Potential Biological Efficiency

This research has shown that improvements in feed conversion efficiency associated with the combined improvements in reproductive rate, carcass weight, hogget lambing, and reduction in ewe mortality and ewe size are considerable. This therefore indicates that any livestock enterprise unable to achieve production levels close to the biological potential will be at a considerable disadvantage.

Further to this, the potential improvement in biological efficiency has important implications for the industry as a whole. For example, the industry could potentially reduce ewe numbers by a large proportion and continue to produce the same level of output. Thus, the competition for sheep grazing land from alternative land uses should not automatically limit the growth potential for the sheep industry.

In coherence with the famous 80/20 Principle[11], another key insight is that the near optimum biological efficiency can be obtained not by increasing any one parameter to maximum limits, but by simultaneously increasing a range of system parameters by more modest amounts. This therefore

[11] The 20/20 Principle (also known as Pareto's Law) asserts that "a minority of causes, inputs or effort usually lead to a majority of the results, outputs or rewards" (Koch, 1998)

suggests that industry performance can be considerably improved without the need for major technology innovations.

7.9.2 Feed Demand Flexibility

In chapter 6, single factor experimentation confirmed that changes to system parameters can have marked changes to the profile of system feed demand. This finding is further reinforced when simultaneously changing a number of system parameters. System feed demand can be changed from being almost constant throughout the year to highly seasonal with large peak feed demands.

7.9.3 System Feasibility

An explicit assumption of this research is that it was normative and model results were based on specified and interacting variables. Also, the purpose of this research was to determine key drivers of feed conversion efficiency and was not concerned with system implementation. However, when interpreting the results of multi-factor experimentation, it is important to consider the likelihood of covariance between system parameters and the feasibility of particular combinations of livestock parameters. For example, depending on specific genetics and husbandry practices it may not be feasible for a 50 kg ewe to have 170% lambing, and for lambs born to these ewes to grow at 400 g/day and be killed at an 18 kg carcass weight.

7.9.4 System Interactions and the Relative Importance of System Parameters

Multifactor experimentation further demonstrated the importance of using a systems-thinking approach. In this research, it was found that while ewe size did have a considerable impact on feed conversion efficiency, the combined effect of lamb growth rate, lambing percentage and lamb carcass weight had a much greater impact. Therefore, similar to the conclusion made by Dickerson (1978), "body size *per se* is of little importance in determining feed conversion efficiency in animal meat production when compared with the functional output per unit of body size in reproduction, growth and body composition". In other words, ewe size alone should not be the primary factor in considering the type of ewe. For example, a 60% increase in ewe weight (from 50 kg to 80 kg) can be compensated by about a 20% increase in lambing percentage (from 110% to about 133%) (see Table 7.9).

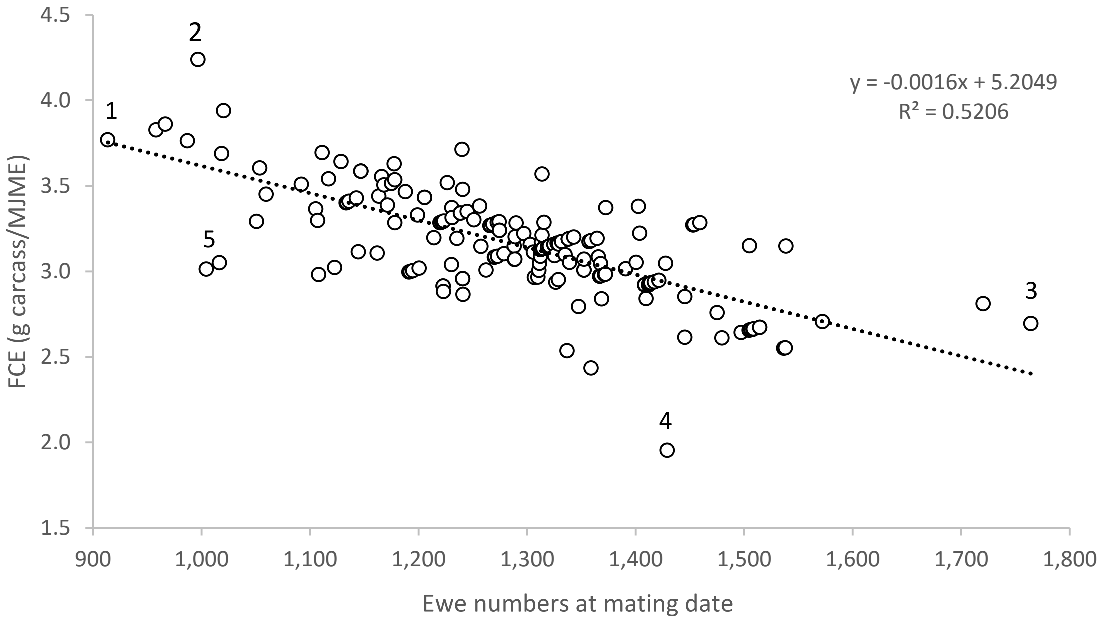
Although lamb growth did impact on feed conversion efficiency, fast growth rates will not make up for the inefficiencies associated with very low carcass weights. It is with higher carcass weight that the benefit of fast growth rate can be captured. However, in considering the combined effect of lamb growth rate and carcass weight, a factor of importance is the mature size of the lamb. In the model, it was assumed that post-weaning growth rate was constant. However, it is well known that, in reality, growth slows as lambs reach maturity (Fitzhugh, 1976; Owens et al., 1993). If ewe size remains constant, increasing carcass weight will increase the weight for maturity relationship and therefore, higher carcass weights should result in slower growth as lambs near maturity.

The increasing importance of lamb growth rate when reproductive rates are higher is consistent with the conclusion of Large (1976, p. 54). As reproductive performance increases, the total energy requirement of lambs relative to the energy requirement from breeding ewes increases, and thus, fast lamb growth and a reduction in the maintenance energy cost of lambs(due to their early slaughter) will have a greater impact on system feed conversion efficiency. From these results, it is clear that in a flock situation, the effect of lamb growth rate on feed conversion efficiency should not be overemphasised, especially when reproductive performance is low.

A key insight is that the importance of system parameters depend on the system context and the performance levels of other system parameters.

7.9.5 Stocking Rate

From analysis of the results of the multifactor experimentation presented in this chapter, feed conversion efficiency was negatively correlated to ewe numbers at mating date (Figure 7.5). For example, from 214 observations, an increase of 100 ewes corresponded to an average reduction of 0.16 g carcass/MJME. Therefore, while individual livestock production parameters can have a positive correlation with feed conversion efficiency, across the range of parameters investigated, maximum feed conversion efficiency of livestock systems is unlikely to be achieved through maximum stocking rate (number of ewes per ha). This is explained in that the primary drivers of system feed conversion efficiency are parameters that reduce maternal feed overhead, most notably being lambing percentage and lamb carcass weight. These parameters effectively transfer the allocation of feed requirement from the ewe to the lamb and, within a fixed feed supply constraint, require ewe numbers to reduce. This general principle that lower stock numbers and higher animal performance will result in higher system feed conversion efficiency was also reported in dairy livestock systems by Jensen et al. (2005).



Production Parameter	Value at point…				
	1	2	3	4	5
Lambing % (lambs tailed/ewe mated)	170%	171%	110%	105%	120%
Pre-Wng LWG (g/day)	450	450	250	250	250
Post-Wng LWG (g/day)	200	200	200	100	100
Ewe Size (kg)	80	50	50	80	65
Lamb Carcass Weight (kg)	24	24	12	12	24
Hgt Lambing % (hgt lambs tailed/total hgt)	60%	121%	60%	0%	60%
Cull Age (years)	7.3	6.3	7.3	10.3	7.3
MA Ewe Mortality Rate (%)	3%	1%	3%	7%	3%

Figure 7.5 The relationship between the number of ewes at mating date and feed conversion efficiency (g carcass/MJME) under different scenario combinations of production parameters

7.10 Summary of Key Findings

There are several 'big picture messages' which have emerged from this research. First, through the combined change to multiple livestock system production parameters, large improvements in system output and biological efficiency are possible, with the feed conversion efficiency of the maximum system scenario being greater than double that of the minimum system scenario. This suggests that farmers have considerable potential to improve the productive output from their farms irrespective of their capacity to influence feed supply. This also implies that, as an industry, there is considerable potential to increase total sheep meat production despite land use constraints and limited feed resources.

In relation to strategies for increasing feed conversion efficiency, a second key message is that factors that reduce maternal feed overheads per unit of output have the greatest impact on feed conversion efficiency. Also, factors that impact on the numerator in the meat output per feed input equation will have the greatest impact on feed conversion efficiency. All else remaining constant, higher lambing percentages and target carcass weight will have a much greater effect on feed conversion efficiency in comparison to lamb growth rate.

A third key message is that, in most cases, simultaneous changes in individual livestock system parameters do not have a simple additive effect on feed conversion efficiency. For example, for lamb growth rate and lambing percentage the combined impact of these parameters was complementary with the effect of lamb growth rate on feed conversion efficiency increasing as lambing percentage increased. In contrast, the impact of pre-weaning and post-weaning lamb growth rate parameters had a less than additive impact on feed conversion efficiency. Understanding such system dynamics is therefore important in planning for efficient production systems.

A fourth key message is that there are many possible system combinations that result in similarly high feed conversion efficiency, i.e. there is more than one way for high system efficiency to be achieved. This means that if, for whatever reason, improvement in one particular production parameter cannot be achieved, this does not necessarily limit the potential of the system to achieve high production efficiency. Also, while the sheep livestock system is complex, through dynamic system interactions, it is possible to "design" a livestock system to both match closely with the feed supply profile and to be efficient at converting feed into meat carcass output.

Through simultaneous changes to system parameters, farmers can also have a very large amount of control on the seasonal profile of feed demand. There is no *a priori* reason why highly efficient livestock production systems are limited to a specific feed demand profile. Therefore, this suggests that through the implementation of the correct production strategies, high feed conversion efficiency can be achievable irrespective of the feed supply context.

An important caveat to the above comments is that these findings do not take into account any specifics about feed in different times of the year having a different cost. In the next chapter, the biological linear programming model is extended to illustrate how these factors can be incorporated within the modelling framework.

Chapter 8
Incorporating Economics

8.1 Introduction

In economics, economic efficiency is defined as the point when the difference between revenue and cost is greatest or when marginal return equals marginal cost (Doll & Orazem, 1984, p. 61). Although the biological or feed conversion efficiency of the livestock production system is a key driver of product output, which is in turn a key factor influencing economic returns, it does not follow that maximising biological efficiency will also maximise economic efficiency. This is because, changes to the livestock system also impact on costs and prices.

Given specific assumptions relating to prices, costs, and feed supply, the purpose of this chapter is to show how the baseline linear programming model can be adapted to investigate trade-offs between biological efficiency and the gross margin return from the sheep enterprise. Whole-of-system gross margin analysis can be a useful approach to determining economic efficiency, with the proviso that the economic efficiency comparisons should relate to a common infrastructure base (Dent et al., 1986, p. 14). That assumption is realistic in relation to the comparisons considered here.

In relation to sheep livestock production, the total gross margin return is defined as the revenue from the sheep livestock enterprise less direct production costs, including the opportunity cost of capital invested in breeding livestock (Morris, Brookes, et al., 1994). Note that while the measure of biological efficiency used in this research relates only to meat carcass output, the gross margin return of the sheep enterprise includes prices and costs relating to the production and sale of both sheep meat (lamb and mutton) and wool.

There are three parts to this chapter. First, the conceptual logic of the extended model is explained and is followed by a description of the methods and assumptions used to convert the base biological linear programming model into an economic model.

The second part of this chapter presents the results of model experimentation. Of the livestock parameters tested in chapter 6 and 7, economic analysis in this chapter is restricted to just four livestock parameters. This is justified in that this chapter is primarily illustrative and focuses on demonstrating how economic factors can be incorporated into the baseline linear programming framework and does not aim at being a full and final investigation into the economic impact of alternative livestock systems. Parameters investigated are lambing percentage, pre-weaning lamb growth rate, post-weaning lamb growth rate, and lamb carcass weight. Comparisons to two physical environments are also presented for illustrative purposes.

In investigating the economic impact of livestock parameters, particular emphasis is placed on the effect of the seasonality of feed demand and on feed costs and the gross margin return per MJME. The rationale for this is that it has been shown in preceding chapters that alternative sheep production systems often result in a considerable shift in the seasonality of feed demand.

In the final part of this chapter some issues relating to model validation are presented, together with a discussion of the findings from model experimentation.

8.2 The Economic Model

To incorporate economics into the baseline linear programming model, the model remained demand-driven. First, the animal feed demands and their seasonality were determined by the initial assumptions as to animal performance. For example, as with the biological model, whole-of-system animal feed demands were determined endogenously within the model based on the feed demands required to achieve specified individual animal performance levels. Total annual supply of feed energy was also fixed at 10 million MJME. However, to extend the model into an economic context, in relation to a specified pastoral feed supply environment, initial feed deficits were also determined by comparing the whole-of-system animal feed demands versus the feed supply from pasture. Deficits were then met, via transfer activities, by transferring feed from periods of excess to shortage at a pre-determined cost. Along with product pricing and animal production cost assumptions, the model thereby calculates for each parameter set both physical output and a net economic output, each expressed per unit of system MJME. This then provides a basis for comparing strategies based on an objective of maximising gross margin from a constrained total supply of feed. The major defining feature of the model is that the cost of feed was determined as a function of the cost of providing feed at particular periods of time as a consequence of the requirement for feed transfer activities.

To extend the biological linear programming model, in total, 181 activities and 128 tie rows were added to the biological linear programming matrix. First, 53 activities were added for feed supplied from pasture growth, with one activity added for total feed supply from pasture and 52 activities added for feed supply from pasture for each week. Activities were then added to reconcile whole-of-system feed demand with feed supply from pasture. 52 activities (one for each week) were added for the pasture feed supply that was surplus to animal requirements and another 52 activities were added for feed transferred to meet animal requirements when feed demand was greater than the feed supplied from pasture. In the model, the balance between pasture feed supply and demand was therefore calculated in weekly periods.

To account for the income associated with wool production, four shearing activities (lambs shorn, hoggets shorn, 2-tooth ewes shorn and MA ewes shorn) and three wool production activities (lambs wool, hogget wool and ewe wool) were added. Further activities that were added included one activity for the total capital value of livestock, six cost activities, eight sales activities and two gross margin activities. Cost activities included feed cost, labour cost, capital cost, shearing cost, animal health cost, and the total direct cost of the sheep enterprise. Sales activities included lamb, mutton and total meat sales as well as lamb wool sales, hogget wool sales, ewe wool sales, total wool sales and total sheep gross income. Of the two gross margin activities, one activity was for a positive gross margin and the other activity was for a negative gross margin.

Of the tie rows that were added to the linear programming matrix, there was one tie row linking total feed demand with total feed supply from pasture. There were also 52 pasture feed supply tie rows linking total feed supply from pasture to feed supply from pasture in each week while a further 52 tie rows linked feed demand, feed supply from pasture, surplus pasture and feed transfer activities for each week. In addition, four tie rows were added to link animals to the shearing activities, three tie rows were added linking animals shorn to the wool production activities, and one tie row was added linking individual animals to the value of livestock capital. One tie row was also added to link feed supply from pasture, surplus pasture and transferred feed to total feed, and four tie rows were added to link each stock class to labour cost, shearing cost and animal cost activities. There was also one tie row linking costs to the total direct cost of the sheep enterprise and eight tie rows linking meat and wool production to meat sales, wool sales and total sheep sales. Last, one tie row was added to link costs and revenues to gross margin returns.

Although economic returns were calculated, in the linear programming model the objective function remained the total kg of meat carcass output and was maximised. A schematic representation of the economic linear programming matrix is shown in Figure 8.1.

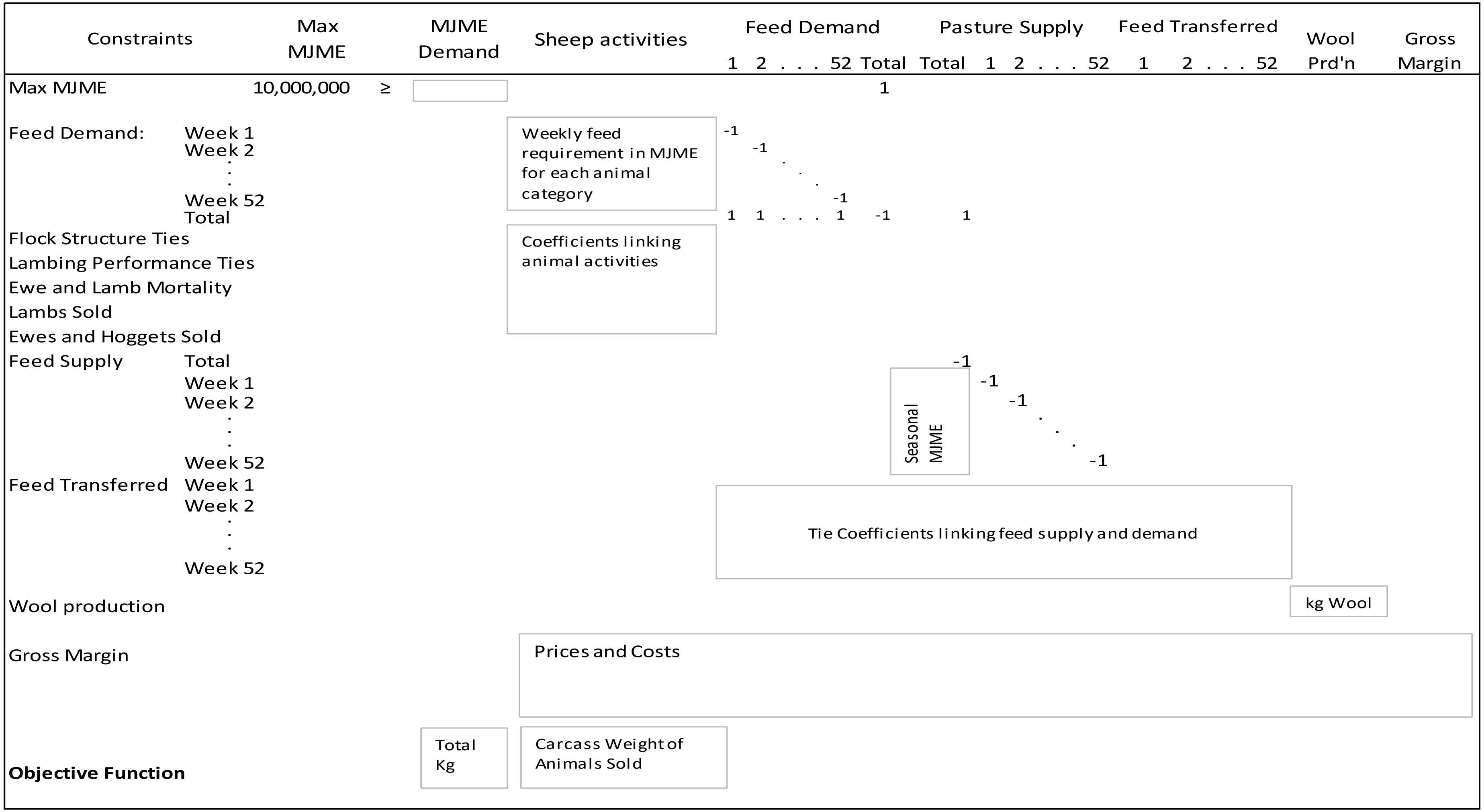


Figure 8.1 Schematic representation of the economic linear programming matrix

Specific assumptions that were required in order to calculate the gross margin returns included mating date, seasonality of feed supply, lamb and mutton schedule price, the opportunity cost of feed, wool production and price, labour costs, animal health costs, shearing costs, and the capital cost of livestock.

8.2.1 Mating Date

Prices and costs show seasonal variation and were reported in relation to a calendar date. To relate these prices and costs to the base linear programming model, which started at ewe mating date, it was assumed that the date of mating was the 10th March.

8.2.2 Pasture Feed supply

In the model, the annual total feed supply[12] from pasture was assumed to be equal to total annual feed demand and was 10 million MJME. The seasonal distribution of feed energy supply was calculated in relationship to pasture growth rate, feed utilisation and feed quality assumptions.

In the baseline model, weekly pasture growth rates (kg DM/ha/day) are from pasture growth rates for dryland pastures in the Canterbury Plains and were from 13 year average growth rate data from the Winchmore Irrigation Research Station (Rickard & Radcliffe, 1976) (Figure 8.2).

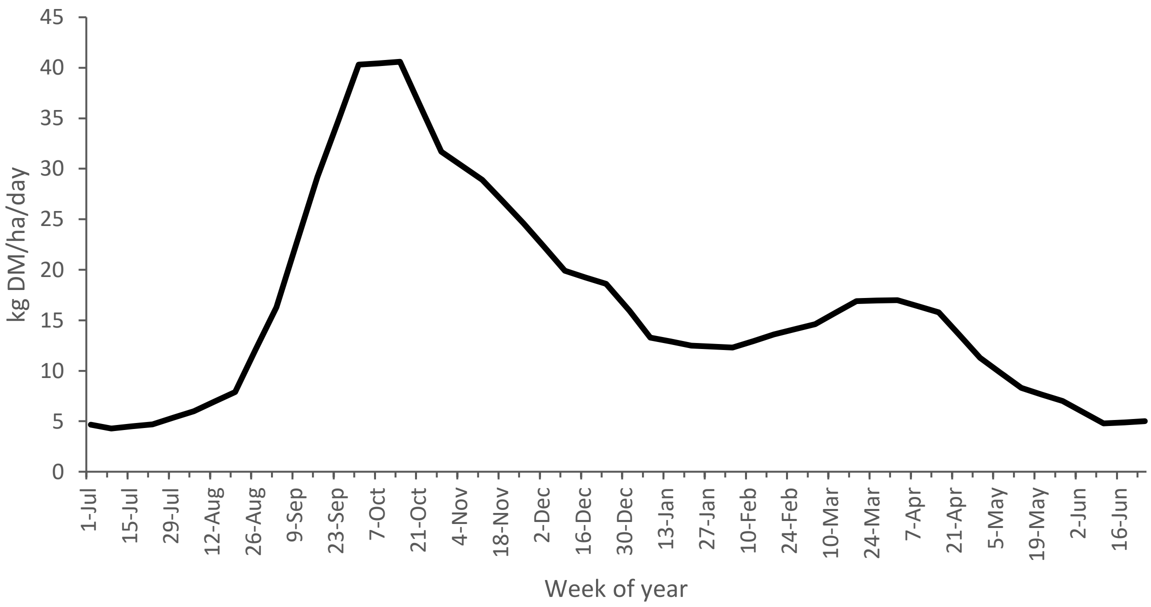


Figure 8.2 Average pasture growth rates (kg DM/ha/day) for dryland pasture at Winchmore Irrigation Research Station over 13 years (Rickard & Radcliffe, 1976)

[12] Note that this refers to feed eaten rather than feed grown

While it was assumed that feed utilisation was 90% and remained constant throughout the year, feed quality estimates were calculated in relation to the seasonal pattern of MJME that is reported by Litherland et al. (2002) and Litherland and Lambert (2007) with feed quality assumed to be lowest in March but assumed to increase over winter to reach a peak in October. In the model, feed quality was calculated for each week of the year using the following equation which was derived from data from Litherland et al. (2002) and Litherland and Lambert (2007):

$$Q = (-0.00018391291754 \times w^3) + (0.01476759686705 \times w^2) - (0.27207212176176 * w) + 10.6189290908036$$

Where;

$Q =$ Feed quality in MJME/kg DM

$w =$ week of year, starting from 1st January

8.2.3 Lamb and Mutton Schedule Price

In the model, the price received per head was calculated by multiplying the meat carcass schedule price ($/kg) by the carcass weight (kg). The meat price per kg was determined based on the week of year in which the animal was sold and the schedule price for that week. The total price per head also included additional payments for wool and pelt.

Weekly schedule prices (in relation to weight and grade) were sourced from Interest.co.nz (2015) and were an average of the South Island 2010-2014 schedule prices for Silver Fern Farms. In this study, price schedules have been based on a single meat processor due to the fact that each meat company in New Zealand has different grade categories with different relativities between carcass weight and price. Silver Fern Farms (SFF) was chosen as this is one of the largest processors of sheep meat in New Zealand (Beef + Lamb New Zealand, 2015; Meat Industry Association of New Zealand, 2009). A five year average of the schedule price was used in order to reduce the effect of drought on schedule price.

The average price schedules for each week of the year and different grades are shown in Appendix E. In relationship to an 18 kg Y or P grade lamb, there was a 24% seasonal variation in schedule price with the $/kg ranging from $4.74 in March to $5.86 in November (Figure 8.3). This is similar to that reported by McDermott (2012) who calculated a mean seasonal variation in PM lamb price of 20% for the 23 year period between 1988 and 2011.

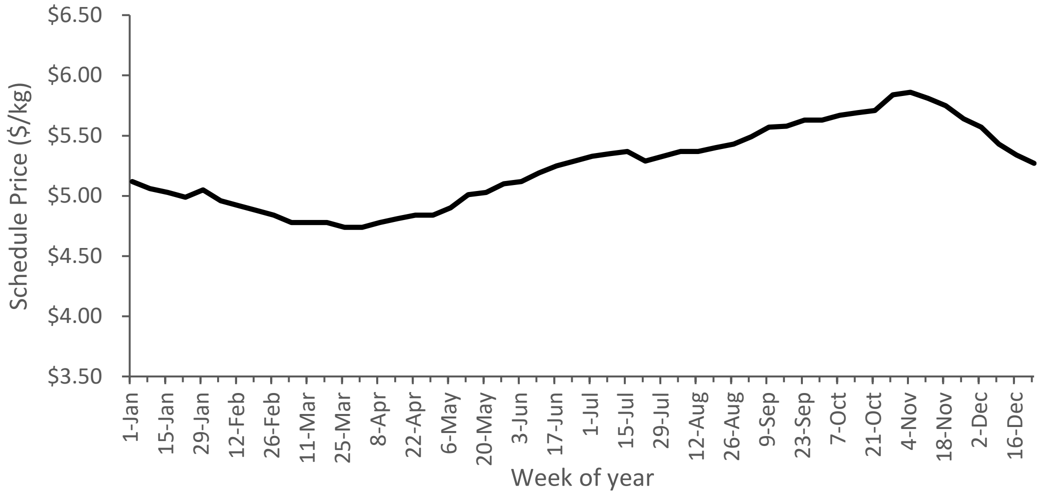


Figure 8.3 Average (2010-2014) weekly Silver Fern Farms schedule prices for an 18 kg Y or P grade lamb

In the baseline model, it was assumed lambs are graded Y, cull hoggets and 2-tooth ewes are graded MX while cull MA ewes are graded MP. Based on the SFF price schedule, maximum price for Y or P grade lambs was when carcass weights ranged between 14 to 23 kg (Figure 8.4).

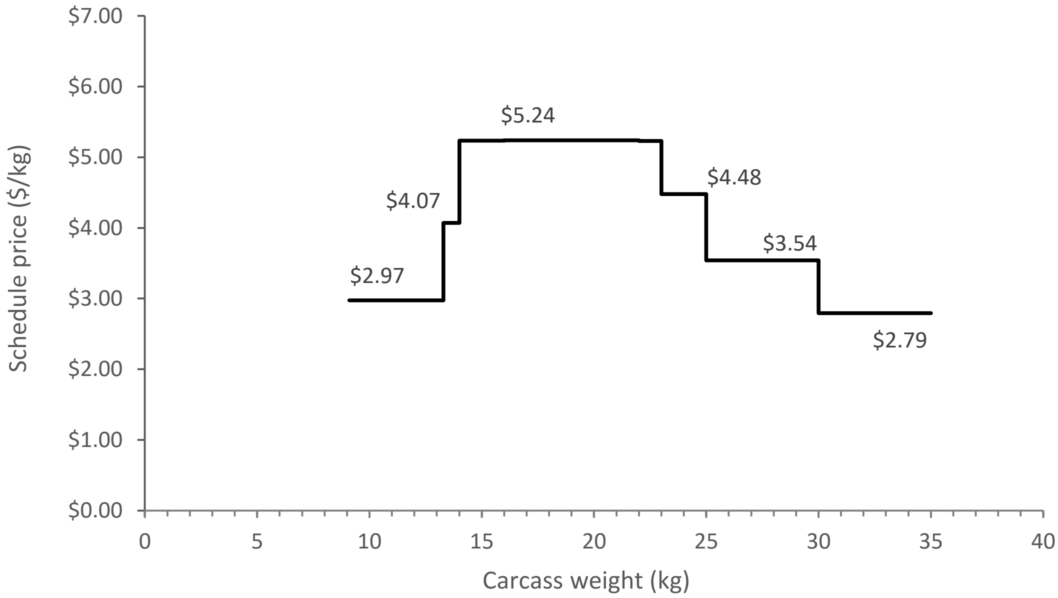


Figure 8.4 Average (2010-2014) Silver Fern Farms schedule prices for Y or P grade lambs for different weight ranges

8.2.4 Wool Production & Price

Wool production assumptions are shown in Table 8.1 and were estimated in reference to the greasy fleece weight of Romney or Romney-cross ewes (Beef + Lamb New Zealand Genetics, 2015; Dobbie, Sumner, Clarke, & Speedy, 1991; Hawker, Dodds, Andrews, & McEwan, 1988; Newman & Paterson, 1991; Trafford & Trafford, 2011). Also, for lambs, it was assumed that 100% of lambs that survive-to-sale were shorn. For ewes and hoggets, it was assumed that all animals that survived to the following season and those animals that were culled post-weaning were shorn.

Table 8.1 Assumed greasy fleece weights (kg/hd) for each stock class

MA Ewes	5.0
2-tooth Ewes	4.5
Hoggets	3.0
Lambs	1.2

The net wool price per kg of greasy wool was based on the 2010-2014 average wool price for South Island finishing-breeding farms and was assumed to be $3.50/kg for lambs, hoggets and ewes.

8.2.5 Costs

Direct costs of the sheep enterprise included the cost of feed, animal health costs, labour costs, shearing costs, and the servicing cost associated with livestock capital.

For pastoral farmers, calculating total feed cost presents a significant challenge (Morris, Brookes, et al., 1994). This is because the cost of feed will depend on how well feed demand matches feed supply. Conceptually, if the seasonal profile of feed energy demand was exactly equal to the profile of feed energy supply from pasture then the cost of feed could be calculated from the costs required to grow the pasture (and there would be no differences in the seasonal cost thereof). These costs might include the capital cost of the land and fertiliser and pasture renewal expenses. However, when the feed demand from the livestock system and the feed supply from pasture growth do not match, additional costs are required to transfer feed. If feed is transferred from surplus pasture, these costs may be due to the costs of making and then feeding out balage. Alternatively, the additional costs required to transfer feed energy may occur from the costs associated from grazing animals off-farm, from transporting feed energy from off-farm sources or from growing brassica or other forage crops.

As feed supply and demand of feed influences the cost of feed, total feed costs cannot be determined as an input. As such, in the model, feed cost was calculated in relationship to the amount of feed transferred. This was determined endogenously within the model and was calculated in reference to a specific pasture growth profile. In the baseline model, the cost of feed transferred to meet feed demand was initially assumed to be 1.4 c/MJME. This is similar to the average cost of transferred feed as calculated by Nicol (1996)(Table 8.2). Although these costs may now be out of date, as the purpose of the economic model as presented in this chapter is for illustration, this fact is not important. In addition to the cost of feed transferred, a base cost of 0.01 cents per MJME was assigned to feed energy grown from pasture.

Table 8.2 Costs (per kg DM and per MJME) of transferring pasture (Nicol, 1996)

		c/kg DM	c/MJME
Silage	-grown	15.0	1.7
	-bought	16.0	1.8
Hay	-grown	15.3	1.8
	-bought	19.3	2.3
Forage Crops		12.3	1.0
Purchased grazing		7-12.0	0.8-1.2
"Saved" pasture		6.5	0.62
Nitrogen "boosted" Pasture		10.3	0.98
AVERAGE		**13.0**	**1.4**

Labour, animal health, and shearing costs are shown in Table 8.3 and were based on the 2010-2014 average costs from the South Island Finishing-Breeding Farm Survey (Beef + Lamb New Zealand Economic Service, 2014). For ewes, hoggets and rams, total costs were calculated from animal numbers at mating date. For lambs, total costs were calculated using survival-to-sale lamb numbers, while shearing costs were calculated from the number of animals shorn.

Table 8.3 Per head costs ($/hd/year) for South Island finishing-breeding farms (Beef + Lamb New Zealand Economic Service, 2014)

	MA Ewes	2-tooth Ewes	Hogget	Lambs	Rams
Labour	5.90	5.90	5.30	3.75	5.90
Animal Health	5.13	5.13	4.70	3.26	5.13
Shearing Costs	6.60	6.60	6.60	5.40	12.00

The servicing cost of livestock capital was calculated by multiplying the estimated value of breeding animals by the interest rate, assumed to be 5.5%. Livestock values for each stock class were calculated from the 2014 New Zealand national average market values from Inland Revenue (2014) and are shown in Table 8.4.

Table 8.4 2014 New Zealand national average market values ($/hd) for sheep (Inland Revenue, 2014)

Hoggets	94
2-tooth Ewes	131
MA Ewes	118
Rams	257

8.3 Experimentation and Results

8.3.1 Baseline Model

Assuming livestock parameters remained at the baseline values used in the biological model, the total gross margin return of the sheep livestock enterprise was 0.97 cents/MJME or $3.10/kg carcass (Table 8.5). With an average meat price of $4.80 per kg carcass and with 31,301 kg of meat being produced, total meat sales was $150,192. Of this, 88% of total meat sales was from lamb while 12% was from mutton. Whole-of-flock shorn wool totalled 8,752 kg from 1,624 lambs, 270 hoggets and 1,224 ewes. This resulted in a total of $30,634 in wool sales which equated to 17% of total sheep gross income.

Table 8.5 Gross Margin of the sheep livestock enterprise for the baseline scenario

	($)	c/MJME
Income		
Lamb Sales	132,306	1.32
Mutton Sales	17,887	0.18
Total Meat Sales	*150,192*	*1.50*
Wool Sales	30,634	0.31
Total Sheep Gross Income	180,826	1.81
Direct Costs		
Feed Costs	26,120	0.26
Animal Health	13,403	0.13
Labour	15,388	0.15
Shearing	18,630	0.19
Servicing Cost of Livestock Capital	10,383	0.10
Total Direct Costs	83,924	0.84
Gross Margin ($)	**96,902**	**0.97**

Assuming total feed energy from pasture growth was equal to the total feed energy demand, and given the assumptions for mating date and pasture growth and quality, the feed profile of energy from pasture did not match the profile of feed energy demand (Figure 8.5). Slow pasture growth during winter resulted in feed demand exceeding feed supply from pasture over the winter period and during the ewe pregnancy period. Despite increased feed demands during the ewe lactation period, very high pasture growth rates during spring resulted in pasture energy supply exceeding feed energy demand.

As a result of this seasonal mismatch between feed demand and feed supply from pasture growth, 17.9% of total feed energy was required to be transferred in order to meet feed energy demand. This resulted in an average feed cost of 0.26 cents/MJME which represents 31% of total direct costs.

Given the baseline livestock numbers (See section 5.2), the total value of capital livestock at mating date was $188,243. Assuming a 5.5% interest cost, this resulted in servicing costs of $10,353 or 12.3% of total direct costs. In total, direct costs equalled 0.83 cents/MJME which was equal to 48% of total sheep gross income (Table 8.5).

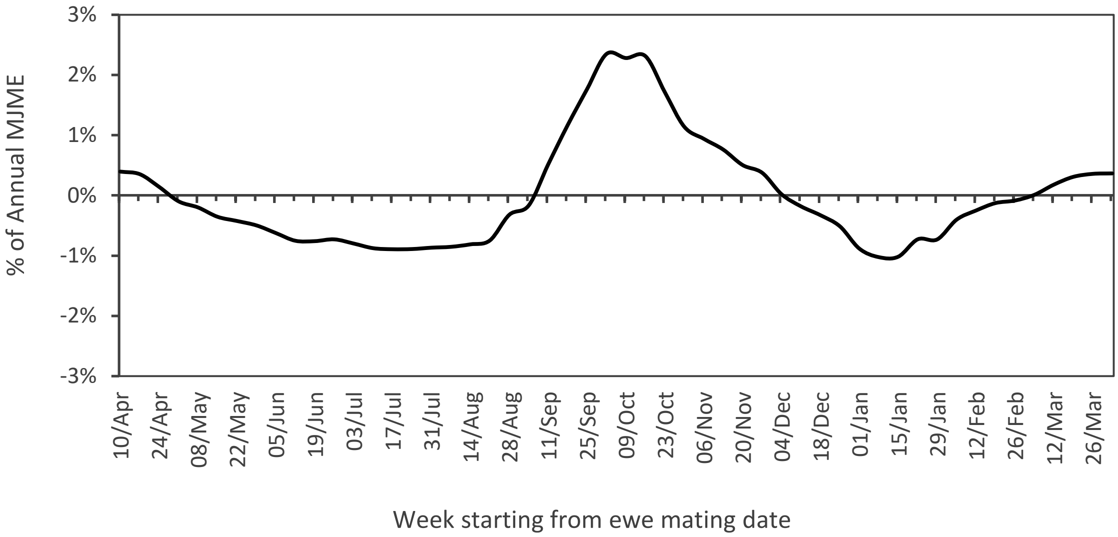


Figure 8.5 Baseline weekly feed energy surplus and deficit in relation to feed energy from pasture growth, expressed as a percentage of annual total feed demand (MJME) starting from ewe mating date.

8.3.2 The Economic Effect of Lambing Percentage

As a result of more lambs, increased lambing percentage increased the income from lamb carcass sales. However, while the total kilograms of lamb carcass increased by 30% (when lambing percentage was increased from 110% to 170%), total income from lamb sales increased by only 29%. This was due to the fact that more lambs were sold later in the season which resulted in a 1% reduction in the average per kg lamb price, due to corresponding reductions in meat carcass schedule prices (Table 8.6). Increased lamb sales was also partially offset by a reduction in mutton carcass and wool sales which decreased by 17% and 7% respectively when lambing percentage was increased from 110% to 170%. While reduced mutton sales were correlated to the reduction in ewe numbers, the reduction in wool sales was dampened by an increase in lamb wool production. Overall, increasing lambing percentage between the minimum and maximum limits increased total gross income from the sheep enterprise by 17%.

Table 8.6 The effect of lambing percentage (lambs tailed per ewe mated) on key whole-of-system economic outputs of the sheep enterprise

Lambing Percentage (lambs tailed per ewe mated)	110%	120%*	130%	140%	150%	160%	170%
Lamb & Mutton Carcass (kg)	30,092	31,301	32,406	33,425	34,346	35,157	35,867
Lamb Carcass (kg)	22,897	24,337	25,665	26,893	28,006	28,994	29,867
Mutton Carcass (kg)	7,195	6,964	6,741	6,533	6,340	6,163	6,000
FCE (g carcass/MJME)	3.01	3.13	3.24	3.34	3.43	3.52	3.59
Wool Production (kg)	8,871	8,752	8,633	8,520	8,414	8,315	8,220
Average Meat Price ($/kg)	4.76	4.80	4.83	4.85	4.87	4.89	4.90
Average Lamb Price ($/kg)	5.45	5.44	5.42	5.41	5.40	5.38	5.37
Average Mutton Price ($/kg)	2.57	2.57	2.57	2.57	2.57	2.57	2.57
Transferred Feed (% of total)	17.7%	17.9%	18.2%	18.5%	18.8%	19.1%	19.4%
Capital Value of Livestock (cents/MJME)	1.94	1.89	1.83	1.78	1.73	1.69	1.65
INCOME (cents/MJME)							
Lamb Carcass	1.25	1.32	1.39	1.45	1.51	1.56	1.60
Mutton Carcass	0.18	0.18	0.17	0.17	0.16	0.16	0.15
Wool	0.31	0.31	0.30	0.30	0.29	0.29	0.29
Total Gross Income	1.74	1.81	1.87	1.92	1.97	2.01	2.05
DIRECT COSTS (cents/MJME)							
Feed Costs	0.26	0.26	0.27	0.27	0.27	0.28	0.28
Animal Health	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Labour	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Shearing	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Servicing Cost of Livestock Capital	0.11	0.10	0.10	0.10	0.10	0.09	0.09
Total Direct Costs	0.84	0.84	0.84	0.84	0.84	0.84	0.85
GROSS MARGIN (cents/MJME)	0.90	0.97	1.03	1.08	1.13	1.17	1.20

* Baseline scenario

Due to the increase in feed demand in the post-weaning period, and in reference to Canterbury dryland pasture growth rates (Figure 8.2), increased lambing percentage resulted in a greater mismatch between feed supply and demand and increased feed deficit from the period from January to March (Figure 8.6). To meet feed requirements, this resulted in an increase in the proportion of feed transferred which subsequently increased whole-of-system feed costs (Table 8.6). For example, when lambing percentage increased from 110% to 170% feed costs increased 9%. However, as a result of reduced ewe numbers, the capital value of livestock reduced 15% which decreased the servicing cost of livestock capital by the same proportion. While reduced ewe numbers also reduced animal health, labour, and shearing costs for the ewe flock, most of these cost savings were offset by increased animal health, labour and shearing costs that were associated with the higher lamb numbers. In total, although the make-up of enterprise costs varied with changes in lambing percentage, the total direct costs of the sheep livestock system remained approximately unchanged (Table 8.6).

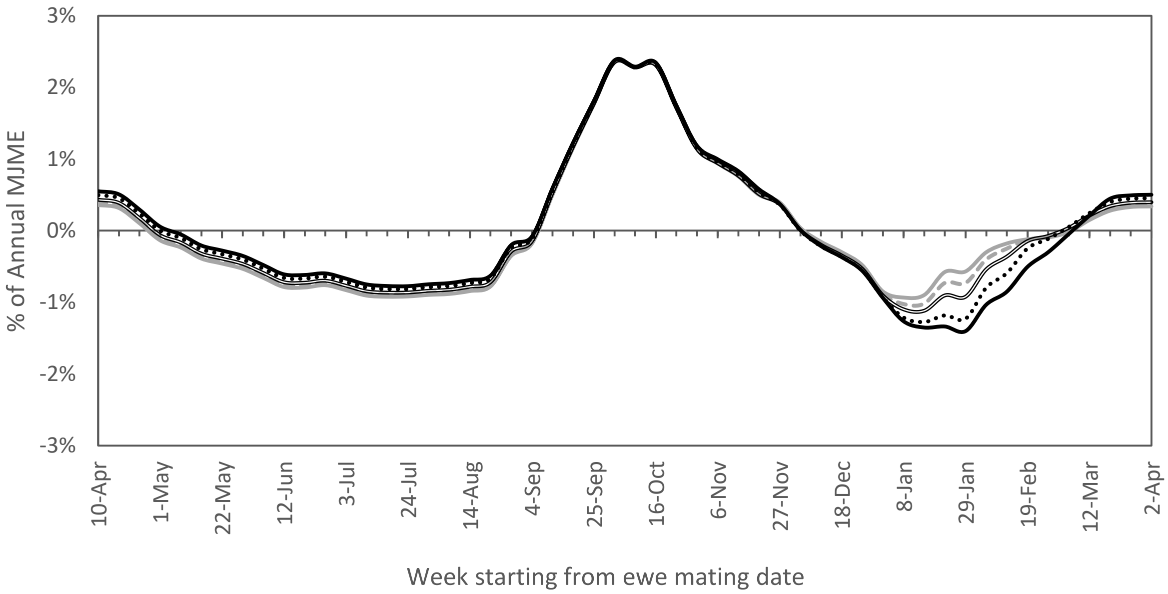


Figure 8.6 The effect of lambing percentage (lambs tailed per ewe mated) at five example lambing rates (—— 110% – – – 120% (baseline) ═══ 130% ········· 150% ━━━ 170%) on whole-of-system weekly feed surplus or deficit (in relation to feed energy from pasture growth), expressed as a percentage of annual total feed demand (MJME) starting from ewe mating date.

Overall, increasing lambing percentage (lambs tailed per ewe mated) from 110% to 170%, increased the gross margin return (cents/MJME) by 33% which was 1.7 times as great as the effect of lambing percentage on biological efficiency (Figure 8.7).

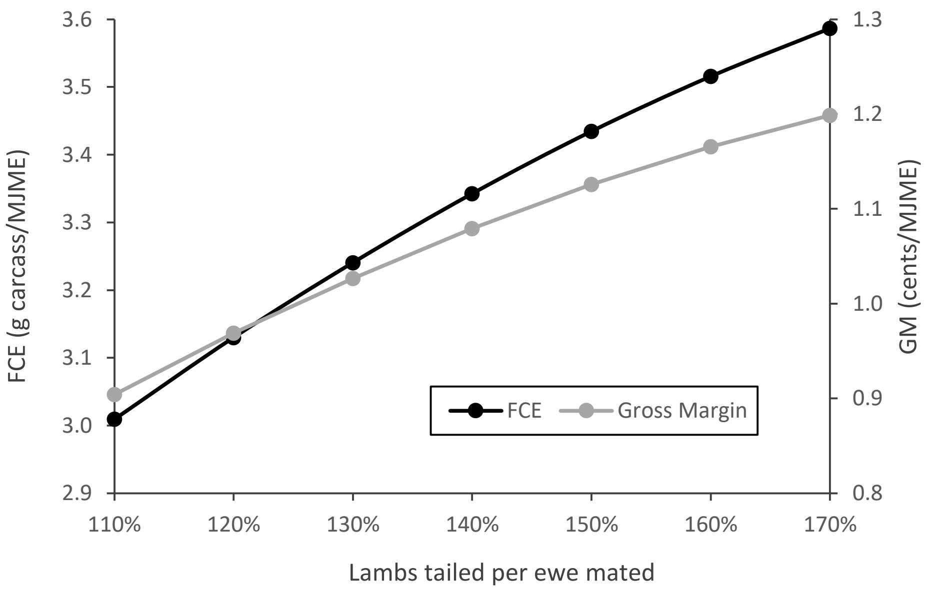


Figure 8.7 The effect of lambing percentage (% lambs tailed per ewe) on feed conversion efficiency (g carcass/MJME) and the gross margin return (cents/MJME)

8.3.3 The Economic Effect of Pre-Weaning Lamb Growth Rate

Increasing pre-weaning lamb growth rate from 250 g/day to 450 g/day increased total gross income by 9% and reduced total direct costs by 12%, which resulted in an increase in the overall gross margin return (cents/MJME) of 30% (Figure 8.8). This improvement was 18.5 times greater than the improvement in feed conversion efficiency (g carcass/MJME). There were two primary reasons for this. First, while total meat output increased just 0.6%, lambs were able to be sold much earlier in the season at higher schedule prices. In total, increasing pre-weaning lamb growth rate from 250 g/day to 450 g/day increased the average per kg meat price for lamb carcass by 12% which, combined with the small increase in total meat sales, resulted in a 13% increase in income from lamb carcass sales (Table 8.7).

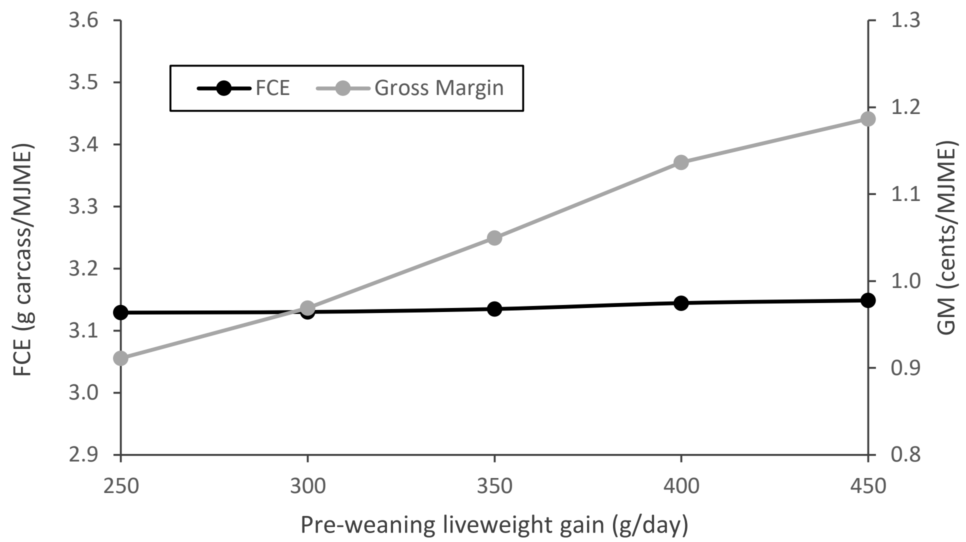


Figure 8.8 The effect of pre-weaning lamb liveweight gain (g/day) on feed conversion efficiency (g carcass/MJME) and the gross margin return (cents/MJME)

The second, more important reason, was that while animal health, labour, shearing and capital service costs all increased by the same rate as the increase in ewe numbers (only 0.63%), increasing pre-weaning lamb growth rate resulted in a 37% reduction in total feed costs. This was because, with improved pre-weaning growth rate, feed supply and demand were more aligned (Figure 8.9). In particular, in relationship to a 10th March mating date and a Canterbury dryland pasture growth rate, increasing pre-weaning growth rate reduced feed surplus in the spring period and reduced feed deficits from December to March. This had a large impact on the amount of feed transferred and on average feed costs. For example, when the average pre-weaning lamb growth rate was 250 g/day, 21% of total feed was required to be transferred in order to meet animal demands. In contrast, when pre-weaning lamb growth rate was 450 g/day only 13% of total feed was required to be transferred between periods.

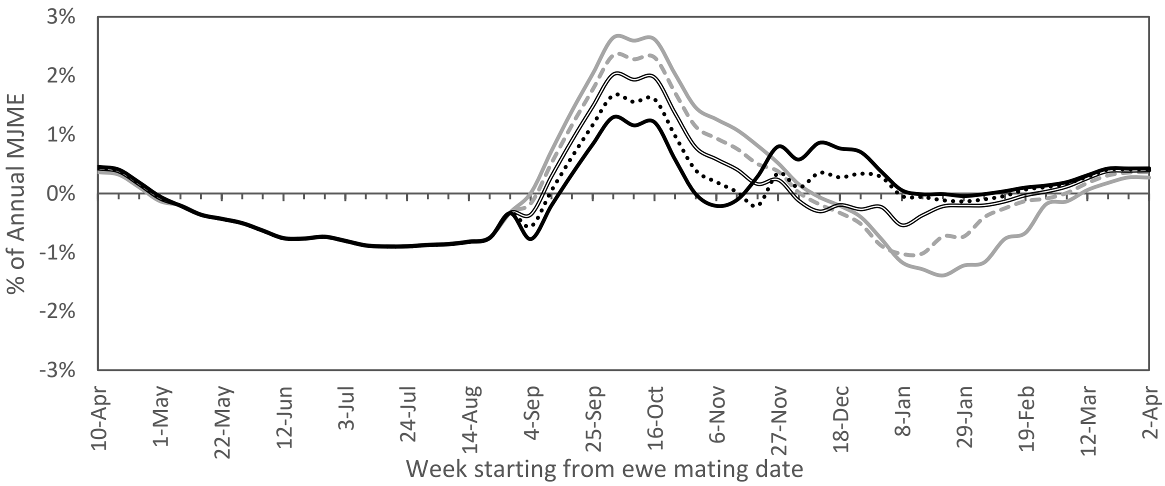


Figure 8.9 The effect of pre-weaning liveweight gain of lambs (—— 250 g/day - - - 300 g/day (baseline) ═══ 350 g/day ········· 400 g/day ━━━ 450 g/day) on whole-of-system weekly feed surplus or deficit (in relation to feed energy from pasture growth), expressed as a percentage of annual total feed demand (MJME) starting from ewe mating date

Table 8.7 The effect of increasing pre-weaning lamb growth rate (g/day) on key whole-of-system economic outputs of the sheep enterprise

Pre-weaning Lamb Growth Rate (g/day)	250	300*	350	400	450
Lamb & Mutton Carcass (kg)	31,290	31,301	31,348	31,444	31,486
Lamb Carcass (kg)	24,329	24,337	24,374	24,448	24,481
Mutton Carcass (kg)	6,962	6,964	6,975	6,996	7,005
FCE (g carcass/MJME)	3.13	3.13	3.13	3.14	3.15
Wool Production (kg)	8,749	8,752	8,766	8,792	8,804
Average Meat Price ($/kg)	4.75	4.80	4.90	5.09	5.24
Average Lamb Price ($/kg)	5.37	5.44	5.57	5.81	6.01
Average Mutton Price ($/kg)	2.57	2.57	2.57	2.57	2.57
Transferred Feed (% of total)	20.9%	17.9%	14.7%	12.8%	13.0%
Capital Value of Livestock (cents/MJME)	1.89	1.89	1.89	1.90	1.90
INCOME (cents/MJME)					
Lamb Carcass	1.31	1.32	1.36	1.42	1.47
Mutton Carcass	0.18	0.18	0.18	0.18	0.18
Wool	0.31	0.31	0.31	0.31	0.31
Total Gross Income	1.79	1.81	1.84	1.91	1.96
DIRECT COSTS (cents/MJME)					
Feed Costs	0.30	0.26	0.22	0.19	0.19
Animal Health	0.13	0.13	0.13	0.13	0.13
Labour	0.15	0.15	0.15	0.15	0.15
Shearing	0.19	0.19	0.19	0.19	0.19
Servicing Cost of Livestock Capital	0.10	0.10	0.10	0.10	0.10
Total Direct Costs	0.88	0.84	0.79	0.77	0.77
GROSS MARGIN (cents/MJME)	0.91	0.97	1.05	1.14	1.19

* Baseline scenario

8.3.4 The Economic Effect of Post-Weaning Lamb Growth Rate

Assuming pre-weaning lamb growth remains at baseline levels, increasing post-weaning lamb growth rate from 100 g/day to 300 g/day increased the gross margin (cents per MJME) by 19% (Figure 8.10). This improvement was predominantly driven by higher enterprise gross income.

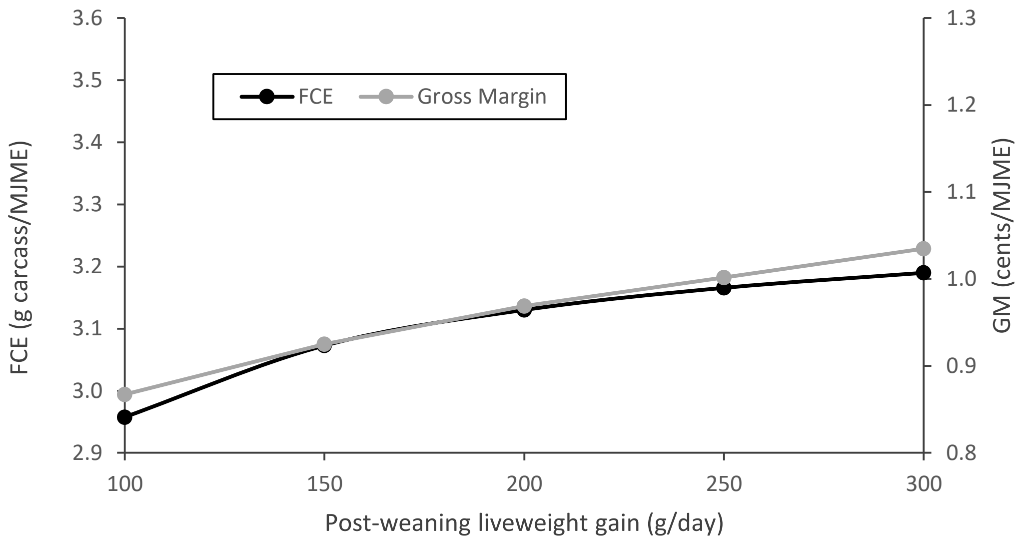


Figure 8.10 The effect of post-weaning lamb liveweight gain (g/day) on feed conversion efficiency (g carcass/MJME) and the gross margin return (cents/MJME)

First, due to the earlier kill date of lambs, average per kg price for lamb carcass increased by 3.8% (Table 8.8). However, this combined with the higher ewe, and hence lamb, numbers increased total income from lamb sales by 12%. Also, due to higher stock numbers, wool production, total income from wool sales, and mutton sales all increased by 7.8%, which was the same percentage increase as the increase in ewe numbers. Overall, when the post-weaning lamb growth rate was increased from 100 g/day to 300 g/day, total gross income from the sheep enterprise increased by 11%.

Looking at costs, increasing the post-weaning lamb growth rate from 100 g/day to 350 g/day reduced total feed costs by 10%. This was because, in relation to Winchmore dryland pasture growth rates and in relation to March 10th mating date, despite an increase in feed deficit early in the post-weaning period, feed deficits in late summer and early autumn were reduced considerably (Figure 8.11). This meant that significantly less feed was required to be transferred. However, because all other costs of the sheep enterprise (shearing, animal health and servicing costs) increased by 8%, despite the reduction in feed costs, total direct costs increased by 2%.

Table 8.8 The effect of increasing post-weaning lamb growth rate (g/day) on key whole-of-system economic outputs of the sheep enterprise

Post-weaning Lamb Growth Rate (g/day)	100	150	200*	250	300
Lamb & Mutton Carcass (kg)	29,577	30,728	31,301	31,656	31,898
Lamb Carcass (kg)	22,996	23,891	24,337	24,613	24,801
Mutton Carcass (kg)	6,580	6,836	6,964	7,043	7,097
FCE (g carcass/MJME)	2.96	3.07	3.13	3.17	3.19
Wool Production (kg)	8,270	8,592	8,752	8,852	8,919
Average Meat Price ($/kg)	4.74	4.75	4.80	4.84	4.90
Average Lamb Price ($/kg)	5.36	5.37	5.44	5.49	5.57
Average Mutton Price ($/kg)	2.57	2.57	2.57	2.57	2.57
Transferred Feed (% of total)	19.2%	18.4%	17.9%	17.6%	17.3%
Capital Value of Livestock (cents/MJME)	1.78	1.85	1.89	1.91	1.92
INCOME (cents/MJME)					
Lamb Carcass	1.23	1.28	1.32	1.35	1.38
Mutton Carcass	0.17	0.18	0.18	0.18	0.18
Wool	0.29	0.30	0.31	0.31	0.31
Total Gross Income	1.69	1.76	1.81	1.84	1.88
DIRECT COSTS (cents/MJME)					
Feed Costs	0.28	0.27	0.26	0.26	0.25
Animal Health	0.13	0.13	0.13	0.14	0.14
Labour	0.15	0.15	0.15	0.16	0.16
Shearing	0.18	0.18	0.19	0.19	0.19
Servicing Cost of Livestock Capital	0.10	0.10	0.10	0.11	0.11
Total Direct Costs	0.82	0.84	0.84	0.84	0.84
GROSS MARGIN (cents/MJME)	0.87	0.93	0.97	1.00	1.03

* Baseline scenario

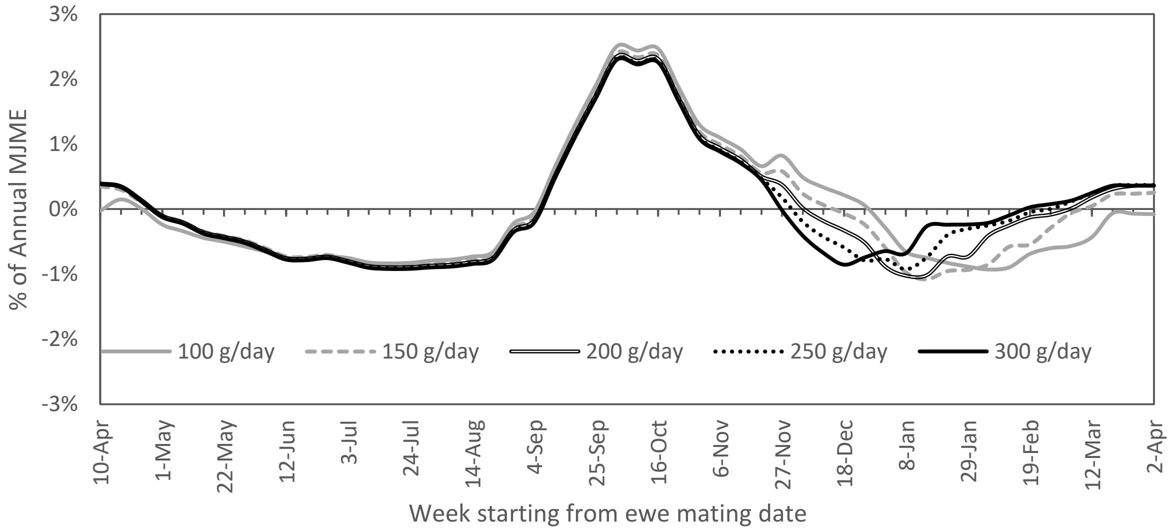


Figure 8.11 The effect of post-weaning liveweight gain of lambs (—— 100 g/day – – – 150 g/day ══ 200 g/day (baseline) ········ 250 g/day ━━ 300 g/day) on whole-of-system weekly feed surplus or deficit (in relation to feed energy from pasture growth), expressed as a percentage of annual total feed demand (MJME) starting from ewe mating date

8.3.5 The Economic Effect of Carcass Weight

In contrast with the effect on whole-of-system feed conversion efficiency (g carcass/MJME), carcass weight had a marked non-linear effect on the gross margin return of the sheep livestock system (Figure 8.12). When carcass weight was increased 2 kg, from 12 kg to 14 kg, the whole-of-system gross margin return (c/MJME) increased by 150%. In comparison, increasing carcass weight by a further 8 kg, from 14 kg to 22 kg, the gross margin return increased by only 15%. However, when carcass weight was increased from 22 kg to 24 kg, gross margin return decreased by 18%. Overall, increasing carcass weight from 12 kg to 24 kg increased whole-of-system gross margin return by 136% and was due to an increase in total enterprise gross income combined with lower total direct costs.

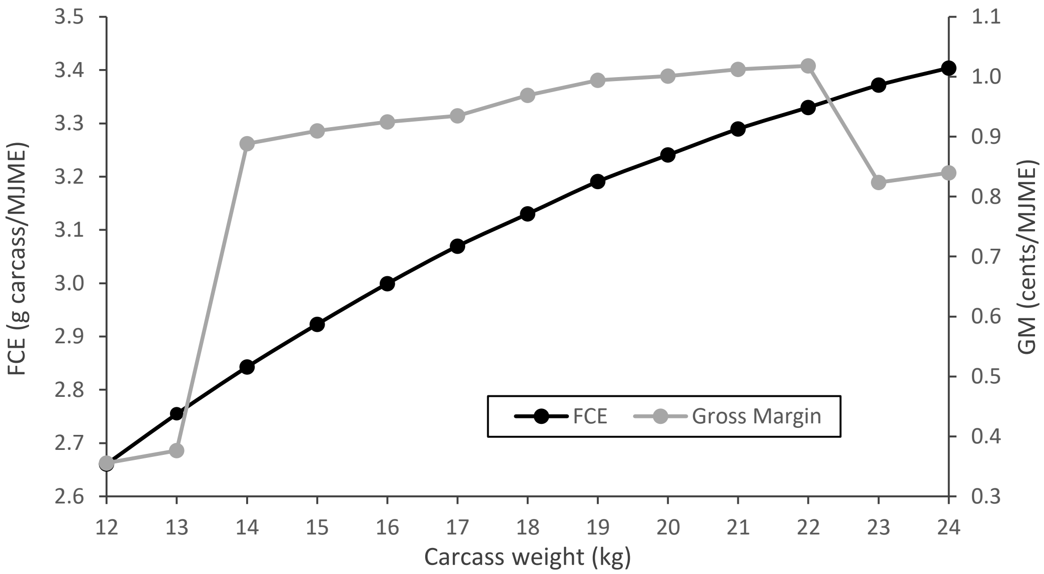


Figure 8.12 The effect of lamb carcass weight (kg) on feed conversion efficiency (g carcass/MJME) and the gross margin return (cents/MJME)

With respect to gross income, higher lamb carcass weights decreased income from mutton and wool sales as a consequence of smaller flock sizes. However, this was offset by a considerable increase in income from lamb sales. While this was heavily influenced by the increase in total lamb carcass output (with lamb carcass increasing 50% when carcass weight was increased from 12 kg to 24 kg), lamb sales was also heavily affected by changes in schedule prices. For example, increasing lamb carcass weight from 12 kg to 15 kg increased the average lamb carcass price from \$3.80 per kg to \$5.67 per kg (Table 8.9).

In relation to costs, while total direct costs of the sheep enterprise decreased 11% when carcass weight increased from 12 kg to 24 kg the make-up of costs changed considerably. This was driven by the shift in the profile of feed demand and by the reduction in ewe numbers. Assuming that pasture growth rates followed the pattern of pasture growth for dryland Canterbury, the considerable

Table 8.9 The effect of lamb carcass weight (kg) on key whole-of-system economic outputs of the sheep enterprise

Carcass Weight	12 kg	15 kg	18 kg*	21 kg	24 kg
Lamb & Mutton Carcass (kg)	26,607	29,230	31,301	32,896	34,040
Lamb Carcass (kg)	18,616	21,758	24,337	26,417	28,025
Mutton Carcass (kg)	7,991	7,471	6,964	6,479	6,014
FCE (g carcass/MJME)	2.66	2.92	3.13	3.29	3.40
Wool Production (kg)	10,043	9,390	8,752	8,143	7,559
Average Meat Price ($/kg)	3.43	4.87	4.80	4.73	4.07
Average Lamb Price ($/kg)	3.80	5.67	5.44	5.26	4.39
Average Mutton Price ($/kg)	2.57	2.57	2.57	2.57	2.57
Transferred Feed (% of total)	16.8%	15.2%	17.9%	20.0%	21.4%
Capital Value of Livestock (cents/MJME)	2.17	2.03	1.89	1.76	1.63
INCOME (cents/MJME)					
Lamb Carcass	0.71	1.23	1.32	1.39	1.23
Mutton Carcass	0.21	0.19	0.18	0.17	0.15
Wool	0.35	0.33	0.31	0.29	0.26
Total Gross Income	1.26	1.75	1.81	1.84	1.65
DIRECT COSTS (cents/MJME)					
Feed Costs	0.25	0.22	0.26	0.29	0.31
Animal Health	0.15	0.14	0.13	0.12	0.12
Labour	0.18	0.17	0.15	0.14	0.13
Shearing	0.21	0.20	0.19	0.17	0.16
Servicing Cost of Livestock Capital	0.12	0.11	0.10	0.10	0.09
Total Direct Costs	0.91	0.84	0.84	0.83	0.81
GROSS MARGIN (cents/MJME)	0.36	0.91	0.97	1.01	0.84

* Baseline Scenario

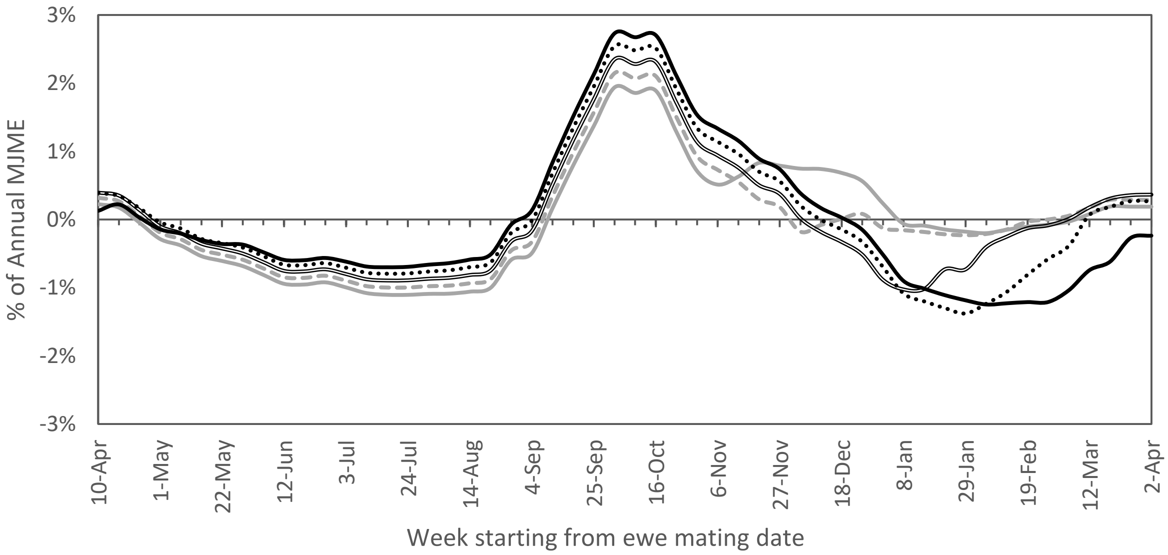


Figure 8.13 The effect of lamb carcass weight (—— 12 kg – – – 15 kg ═══ 18 kg (baseline) ········ 21 kg ━━━ 24 kg) on whole-of-system weekly feed surplus or deficit (in relation to feed energy from pasture growth), expressed as a percentage of annual total feed demand (MJME) starting from ewe mating date.

increase in post-weaning feed demands increased the requirement to transfer feed by 28% when carcass weight was increased from 12 kg to 24 kg (Figure 8.13). Assuming it costs 1.4 cents/MJME to transfer feed, this translated into a 27% increase in total feed costs. However, this increase in cost is compensated by a reduction in animal health, shearing and capital servicing costs which all reduced by 24.7%, which was the same rate as the change in ewe numbers.

8.3.6 The Importance of the Supply Context

The economic effect of livestock production parameters is specific to the feed supply context. To demonstrate this, the effect of livestock production parameters on whole-of-system gross margin return was compared under dryland and irrigated feed supply scenarios (Figure 8.14).

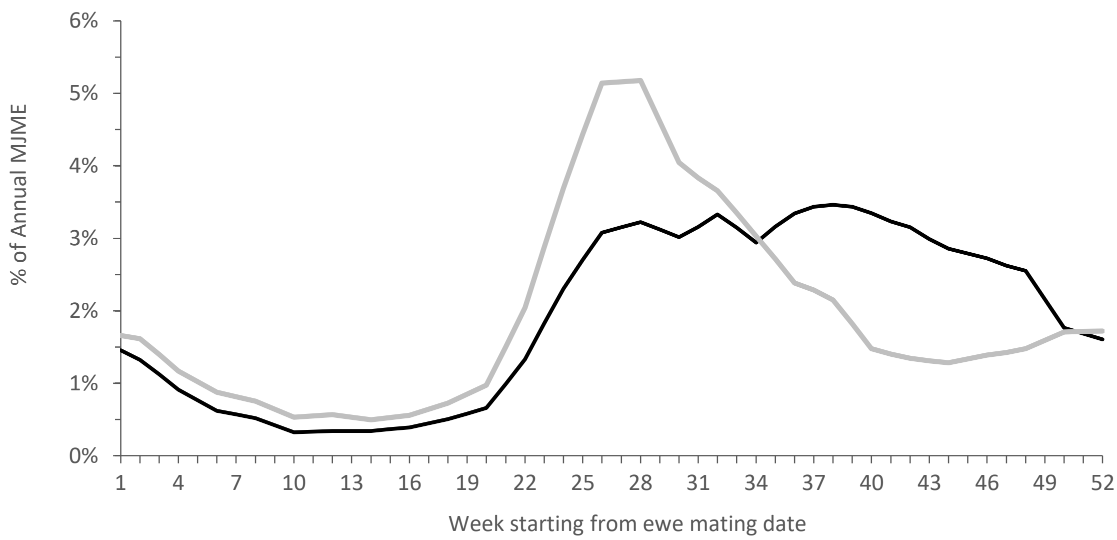


Figure 8.14 The weekly feed supply from pasture, measured as the percentage of total annual MJME, for Winchmore dryland (——) and Winchmore irrigated (——) pastures

It was found that the specific feed supply context had a major effect on the relationship between livestock parameters and the enterprise gross margin returns. For example, under the Canterbury dryland profile of feed supply, increasing lamb carcass weight from 12 kg to 24 kg increased enterprise gross margin return by 133%. In contrast, under the Canterbury irrigated pasture growth profile, increasing lamb carcass weight from 12 kg to 24 kg increased enterprise gross margin return by 268% (Table 8.10). Similarly, in contrast to the large increase in gross margin return under a dryland profile of feed supply, increasing pre-weaning lamb growth rates under the Canterbury irrigated feed supply scenario only increased the enterprise gross margin return by 3% (Table 8.11).

Table 8.10 The effect of lamb carcass weight (kg) on key whole-of-system economic outputs of the sheep enterprise for Canterbury dryland and Canterbury irrigated feed supply contexts

Feed Supply Profile	Canterbury dryland		Canterbury irrigated	
Carcass Weight	12 kg	24 kg	12 kg	24 kg
Lamb & Mutton Carcass (kg)	26,607	34,040	26,607	34,040
Lamb Carcass (kg)	18,616	28,025	18,616	28,025
Mutton Carcass (kg)	7,991	6,014	7,991	6,014
FCE (g carcass/MJME)	2.66	3.40	2.66	3.40
Wool Production (kg)	10,043	7,559	10,043	7,559
Average Meat Price ($/kg)	3.43	4.07	3.43	4.07
Average Lamb Price ($/kg)	3.80	4.39	3.80	4.39
Average Mutton Price ($/kg)	2.57	2.57	2.57	2.57
Transferred Feed (% of total)	16.8%	21.4%	24.0%	15.6%
Capital Value of Livestock (cents/MJME)	2.17	1.63	2.17	1.63
INCOME (cents/MJME)				
Lamb Carcass	0.71	1.23	0.71	1.23
Mutton Carcass	0.21	0.15	0.21	0.15
Wool	0.35	0.26	0.35	0.26
Total Gross Income	1.26	1.65	1.26	1.65
DIRECT COSTS (cents/MJME)				
Feed Costs	0.25	0.31	0.35	0.23
Animal Health	0.15	0.12	0.15	0.12
Labour	0.18	0.13	0.18	0.13
Shearing	0.21	0.16	0.21	0.16
Servicing Cost of Livestock Capital	0.12	0.09	0.12	0.09
Total Direct Costs	0.91	0.81	1.01	0.73
GROSS MARGIN (cents/MJME)	0.36	0.84	0.25	0.92

Table 8.11 The effect of pre-weaning lamb growth rate (g/day) on key whole-of-system economic outputs of the sheep enterprise for Canterbury dryland and Canterbury irrigated feed supply contexts

Feed Supply Profile	Canterbury dryland		Canterbury irrigated	
Pre-weaning Lamb Growth Rate	250 g/day	450 g/day	250 g/day	450 g/day
Lamb & Mutton Carcass (kg)	31,290	31,486	31,290	31,486
Lamb Carcass (kg)	24,329	24,481	24,329	24,481
Mutton Carcass (kg)	6,962	7,005	6,962	7,005
FCE (g carcass/MJME)	3.13	3.15	3.13	3.15
Wool Production (kg)	8,749	8,766	8,749	8,766
Average Meat Price ($/kg)	4.75	5.24	4.75	5.24
Average Lamb Price ($/kg)	5.37	6.01	5.37	6.01
Average Mutton Price ($/kg)	2.57	2.57	2.57	2.57
Transferred Feed (% of total)	20.9%	14.7%	17.0%	26.3%
Capital Value of Livestock (cents/MJME)	1.89	1.89	1.89	1.89
INCOME (cents/MJME)				
Lamb Carcass	1.31	1.47	1.31	1.47
Mutton Carcass	0.18	0.18	0.18	0.18
Wool	0.31	0.31	0.31	0.31
Total Gross Income	1.79	1.96	1.79	1.96
DIRECT COSTS (cents/MJME)				
Feed Costs	0.30	0.22	0.25	0.38
Animal Health	0.13	0.13	0.13	0.13
Labour	0.15	0.15	0.15	0.15
Shearing	0.19	0.19	0.19	0.19
Servicing Cost of Livestock Capital	0.10	0.10	0.10	0.10
Total Direct Costs	0.88	0.79	0.83	0.96
GROSS MARGIN (cents/MJME)	0.91	1.05	0.97	1.00

8.4 Model Validation

In relation to the validity of the economic model presented in this chapter, it must be emphasised that the aim of the economic extension to the baseline linear programming model was primarily illustrative with the purpose being to show how economic considerations can be incorporated into the baseline biological model. Model validity must therefore be assessed in relation to this purpose and is therefore primarily concerned with the conceptual logic of the economic extensions to the biological model and of the logic of measured results. There are several logical considerations that are worth discussing.

The first relates to the appropriateness of the measure of economic output used in the model. In this model, economic outcome was measured in respect to the net return from the sheep enterprise per

MJME. Although these were average returns, when comparing systems, the differences were the marginal returns from reconfiguration. Hence as long as all costs of reconfiguration are included, then they do provide economic optima.

In the model, a major conceptual idea is that as the mismatch between feed supply and demand increases, the requirement for increased feed transfer activities will result in an increase in total feed cost. Although the cost of this transferred feed will have an impact on economic outcomes, as this chapter is illustrative, the choice of 1.4c /MJME is not important.

A further validation issue relates to the fact that the model does not allow for small feed surpluses or deficits to be met via changes in pasture cover[13]. This assumption may result in the cost of transferred feed being overstated. This is because even if feed demand is greater than feed supply from pasture growth for one week, the full cost of 1.4 c/MJME was imposed for feed transferred over that week. However, in practice, small changes between feed supply and demand go largely unnoticed as they are accounted for by changes in average pasture cover. However, if feed is transferred by way of increased pasture cover, a factor that must also be considered is the effect of changes in feed quality due to pasture senescence and decay (Romera & Doole, 2015). Similarly, another validation consideration is that the model does not account for feed energy losses associated with feed transfer activities.

These validation concerns are due to the change in purpose and the extension of the biological model to incorporate feed supply which has resulted in the system boundary shifting from the level of the livestock system to the farm system and the requirement to account for plant-animal interactions. Notwithstanding, given that this research has been undertaken in the context of strategic farm planning, the need to incorporate detailed interactions between plant and animal has less importance. Therefore, in summary, the results presented in this chapter are explainable and are assessed as valid for the purpose of this chapter which is essentially illustrative.

8.5 Discussion

In chapters 6 and 7, it was shown that the efficiency impacts of alternative performance levels and livestock systems were considerable. Nevertheless, biological efficiency impacts, when measured in percentage terms, were small compared to the financial impact of changes in schedule price. What is therefore clear is that while individual farmers can have a major influence on their own individual fate through ensuring that they farm efficiently in a production context, the final economic outcome

[13] This is defined as the average pasture mass (kg DM/ha) over the whole grazing area (Nicol, 1996). When feed demand is less than feed supply from pasture growth, pasture is "stored" *in situ* increasing pasture cover. When feed demand is greater than feed supply from pasture growth, pasture covers are "mined" as more feed is eaten than grown.

from farming may be determined by the market price for meat carcass. While this was also found to be the case in other livestock systems (Woodford, 1997, p. 185), this message is in contrast to the findings by Deloitte (2011) who conclude that top quartile farmers did not receive any major price differential on their livestock outputs in comparison to bottom quartile farmers. However, variance in conclusions are reconciled by overlying social factors and the reality that for individual farmers, influencing market price is a much greater challenge then ensuring efficient production. What this therefore points to is the vast opportunity which lies ahead for livestock farmers who are both biologically efficient and who, as an industry, are able to capture added value and increase product price.

The effect of livestock parameters on enterprise gross margin return depends largely on the specific feed supply context. This hints to the idea that specific livestock systems will have their own specific environmental niche.

8.6 Summary of Key Findings

1. Livestock parameters can have very different relationships between whole-of-system feed conversion efficiency and gross margin return. For example, lambing percentage increased gross margin returns by approximately equal to the increase in feed conversion efficiency while pre-weaning growth rate increased gross margin returns by a factor 18.5 times greater than the increase in feed conversion efficiency.

2. Therefore, livestock parameters that had a high impact on biological efficiency did not always have a high impact on gross margin return.

3. Conversely, parameters which have a small impact on biological efficiency can have a major impact on gross margin return

4. In relationship to a specific environmental and economic environment, the factors impacting income, costs, and thus total gross margin returns will vary considerably depending on the livestock parameter that is changed. For example, while increased production output is an underlying driver, in the case of carcass weight, gross margin return was strongly impacted by the relative schedule price throughout the year and the price premium paid in relation to weight grade.

5. The effect of livestock parameters on gross margin return is highly dependent on the specific feed supply context. For example, while increasing pre-weaning lamb growth rate from 250 g/day to 400 g/day increased the gross margin return (cents/MJME) of the sheep enterprise by 30% under a Canterbury dryland feed supply scenario, the gross margin return only increased by

3% under a Canterbury irrigated feed supply scenario[14]. This was due to changes in the match between feed supply and demand and associated changes in feed costs.

6. Ewe numbers were not a good predictor of economic return. While lower ewe numbers reduced gross income from mutton and wool sales this was offset by lower costs for capital, animal health and shearing.

[14] These numbers might have changed if buying in store lambs was allowed for

Chapter 9

Review, Synthesis, and Conclusions

9.1 Introduction

The purpose of this final chapter is to review and integrate the findings and insights from earlier chapters, and to use these findings and insights as a basis for strategy development that can provide decision guidance, both at the level of the farm, and also at the level of the industry. Model limitations, future research, and contributions to knowledge are also discussed. The thesis concludes with a restatement of the research questions and a summary of the answers to these questions.

9.2 Review

The initial chapter to this thesis set the research background and outlined the research aim, the research questions, and provided an introduction to the underlying research methodology. The research was defined as a demand-driven modelling study undertaken following the Management Science/Operations Research methodology, which in-turn, is based on the problem-solving approach. A key perspective of this study is that of systems-thinking and the idea that when a new component is added to a system, a new dynamic is created which, due to systems interactions, is likely to impact on overall system performance. However, the level of analysis and definition of the systems boundary is based on purpose.

In the second chapter of this theses, it was stated that efficiency is a measure of how well resources are used in a given activity. The concept of biological efficiency was then discussed together with an explanation of livestock production and how the biological efficiency of livestock systems are analysed within the context of pastoral production. Following a description of modelling and of the different modelling techniques that are available, a summary of different livestock models was then provided. It was then argued that, for the purpose of farm planning, it is important to understand how changes to the livestock system influence both feed conversion efficiency and the seasonality of feed demand. In other words, a demand-driven systems model at the level of the livestock sub-unit of the farm system is required.

The focus of this research is on sheep meat production systems. In Chapter 3, key parameters of the sheep livestock system were discussed and the possible impact on feed conversion efficiency and seasonality of feed demand was reviewed. It was concluded that while there are many studies that have investigated how various parameters of the livestock system impact on specific measures of biological efficiency, such studies have either taken a component level of analysis or have not investigated the associated impact on the seasonality of feed demand.

Chapter 4 outlined the specific modelling technique that was used in this research and explained the assumptions used in the construction of the baseline linear programming model. The base model was defined as being a demand-driven deterministic steady-state enterprise level model and was set up in reference to a self-replacing sheep breeding-finishing sheep livestock system with individual parameters based on industry average performance levels.

In Chapter 5, the results of the baseline model were presented. This chapter also outlined the process used to verify and validate this model and discussed issues relating to model validity.

In Chapter 6, model experimentation was undertaken to test the individual impact of lambing percentage, pre-weaning lamb growth rate, post-weaning lamb growth rate, ewe size, target carcass weight, hogget lambing, age of ewe culling, and mortality rate on meat output, feed conversion efficiency, ewe numbers and the seasonality of feed demand.

In Chapter 7, the effect of simultaneous changes in livestock parameters was explored. Due to the number of possible scenarios, experimentation focused on testing the combined effect of related parameters and from questions that arose from one-at-a-time experimentation.

Whereas biological efficiency can be evaluated within a generic framework which applies across a broad range of contexts, economic efficiency requires acknowledgement of the specific contextual conditions relating to the seasonal cost of feed and seasonality of product prices, both of which will vary depending on location and year. Subsequently, the purpose of Chapter 8 was to demonstrate how the baseline biological model could be adapted to incorporate economic factors. It was noted that the specific contextual situations presented in the chapter were illustrative for the purpose of demonstrating the capacity and flexibility of the model.

9.3 Synthesis

In this study, linear programming has proved to be a relatively simple and useful framework for the analysis of biological efficiency within a whole-of-systems context. The benefit of the biological model developed in this study is that it is a generic sheep livestock model and has relevance across a range of physical environments. Another important benefit of the model is that analyses are based in relation to a fixed supply of feed. However, there are several important limitations.

The first major restriction of the analytical framework is that it is deterministic and does not capture the stochastic nature of the bio-physical world. This can have important consequences. For example, Cacho and Bywater (1994) compared the results of a stochastic model against a deterministic model of a self-replacing sheep flock. It was found that in the deterministic model, maximum gross margin was 13% higher than the stochastic model.

Another aspect of stochasticity and another limitation of this research relates to the fact that all animals within a particular category are assumed to lamb at the same date and to grow at the same rate. While this should not affect biological efficiency, an increased lambing spread will dampen the whole-of-flock seasonality effects.

A third limitation is that this research uses a steady-state framework and does not account for production responses associated with the implementation of recommended management strategies. For example, in agriculture, sheep are both the product and the means of production. Selling ewe lambs for meat reduces the potential number of replacement ewes and therefore reduces the "means of production" in the following season. The implication is that increasing livestock numbers requires limiting short term production (Jarvis, 1974). Conversely, changes to the livestock system that result in reductions in ewe numbers should therefore increase short term production.

This research is also aimed at determining relative efficiency, and does not go as far as identifying how system parameters are achieved. For example, increasing lambing percentage to very high levels may prove difficult for managers to achieve as this is dependent on animal biology. In contrast, increased carcass weight can often be achieved by delaying sale date which is largely in the control of managers. The ease with which management strategies can be implemented may therefore have considerable bearing to which strategies are adopted by management.

Similarly, another limitation of this research is that the model has been developed as a guide to strategy and has not been developed to identify optimal solutions within a tactical context. In particular, while the model measures the impact of individual parameters on system performance, it does not address the specifics of how these system performances can be achieved. For example, analysis is at the level of the livestock system (rather than at the level of the farm). This is a strength of the model but is also a limitation. The model therefore cannot account for plant-animal interactions and does not moderate animal performance levels in relationship to the availability and quality of feed supply. In summary, the model does not address how feed supply can be provided or managed so that feed demands are met and animal performance parameters can be achieved.

For the purpose of limiting the scope of this study, investigations were limited to self-contained breeding-finishing sheep systems. Therefore, this research did not investigate the feed conversion efficiency impact of purchasing in replacement ewe lambs or from trading livestock between farms. Further to this, investigations were also limited to exploring the impact of only eight key production parameters. However, there are many more production parameters and that the choice of included parameters was judgemental and was made in discussions between the author and the supervisors of this thesis. It is therefore acknowledged that further parameters could have been investigated and that this is an area for further research.

9.4 Contribution to Knowledge

This research contributes to knowledge in a number of ways. First, this research represents a paradigm shift in livestock modelling and the development of a demand-driven linear programming model has provided a novel approach for the generic assessment of the biological efficiency of livestock production systems.

Second, this research shows how livestock parameters impact on the feed conversion efficiency of the livestock system as a whole. This research is also different in that it has been the first study to quantify the impact of a range of sheep livestock production parameters to *both* whole-of-system biological efficiency *and* feed demand seasonality.

Another contribution to knowledge is that this research has demonstrated the use of linear programming to explore trade-offs between biological efficiency and the economic returns of different sheep livestock production systems.

In summary, it is suggested that the models presented in this thesis can be a powerful tool both in assessing system level impacts of particular animal performance, and in guiding R&D programs.

9.5 Further Research

Areas for future research and further extensions to the model include:

1. The application of the biological and economic linear programming models to diverse New Zealand and international contexts, and by solving for feed supply, to use the model to predict the optimal sheep system for a particular profile of feed supply.

2. Modelling and testing the impact of a greater number of livestock production parameters including, but not limited to, ram size, weaning age, lamb survival, birth rank proportions, seasonal liveweight variation, lambing spread, relative lamb growth rate between each animal category, and the purchase of store lambs from off-farm.

3. Testing a greater number of system scenarios. For example, in this research only a few of the many possible combinations of livestock system parameters were tested in respect to their impact on feed conversion efficiency and the seasonality of feed demand. There is potential to

run thousands of different permutations and to test the effect of system parameters under different scenarios. The effect of each system parameter for all conceivable system configurations could then be determined using full regression analysis.

4. In this research, feed demands were modelled starting at ewe mating date. An area of further research is to extend the capability of the linear programming model to select optimal mating dates for a given profile of feed supply and to investigate how the livestock system and associated seasonal profile of feed demand influences optimal mating date.

5. While this research has shown how the biological model can be extended to incorporate economics and has, for illustrative purposes, shown the effect of four system parameters on whole-of-system gross margin returns, an area for further research is to investigate a wider range of livestock system parameters.

6. In relation to the economic model, another system parameter that could be investigated as part of future research would be the cost of feed.

7. Use of the economic model to calculate the price premiums required for profitable counter-seasonal production for a range of feed and cost environments.

8. The economic model as it stand focusses on meeting feed deficit through feed transfer activities. An idea for further development is to reconfigure the model so that the supply of feed is able to be increased through feed augmentation activities. These could include feed purchases or nitrogen supplementation, with constraints on the level of these activities. The 'base supply' of pastoral feed would remain constrained. This would then show, for different strategies, the whole-of-farm gross margin (or the gross margin per MJME of 'base supply').

9. Currently the economic model does not attribute energy losses to feed transferred. As part of further developments to the model, a feed transfer loss of MJME could be incorporated.

9.6 Conclusions

In the introductory chapter of this thesis four major research questions were laid out. The responses to these questions are now summarised in this final section:

1. <u>How do key production parameters of the sheep livestock system impact on whole-of-system feed conversion efficiency?</u>

There are a suite of management options that can increase the feed efficiency of the sheep livestock enterprise by reducing the proportion of feed energy expended on animal maintenance and increasing the proportion expended on production. Most management strategies for improving biological efficiency were found to be associated with reducing the maternal overhead feed costs per unit of meat carcass output. By a large margin, the most important factors were lamb carcass weight and ewe lambing percentage. Other important parameters were hogget lambing and ewe size. A finding that was not intuitively obvious, was that lamb growth rate (particularly pre-weaning growth rate) did not result in large increases in whole-of-system feed conversion efficiency due to complex but explainable system interactions.

In general, changes to livestock production parameters did not result in linear improvements in feed conversion efficiency. Rather, there was a notable decline in the additional benefit for each additional change in livestock performance. In addition, whole-of-system improvements from a change in multiple parameters can be less than the effects obtained through simple addition of individual parameter effects. For example, it was found that simultaneous changes in system parameters often did not result in an additive effect on feed conversion efficiency. Rather, the effect on feed conversion efficiency and the seasonality of feed demand was either less than additive or more than additive. Therefore, in relation to both specific on-farm strategies and R&D research programs, a cautionary conclusion from this research is the importance of assessing the impact of individual production parameters in relation to the overall system rather than just to the specific component.

Another key conclusion is that moderate improvements in multiple system parameters tend to result in a greater improvement in overall system efficiency relative to an extreme improvement in a single production parameter. It is therefore clear that major improvements in farm productivity require a focus on improvements in multiple system parameters.

2. <u>What is the impact of increasing system production parameters on the seasonality of whole-of-system feed demand?</u>

Improving individual animal performance parameters can lead to major seasonality impacts which may not be intuitively obvious, but which need to be factored into both farm production strategies and research programs. By manipulating a range of different parameter combinations, system feed demand can be changed from almost constant throughout the year to highly seasonal with large peak feed demands. The vast changes in the seasonality of feed demand therefore has major implications for the management of feed supply if specified production levels are to be achieved and suggests that careful consideration of seasonality impacts is required prior to implementing livestock system changes.

3. For total system feed demand to remain unchanged, how do key livestock production parameters impact on the number of breeding ewes able to be kept?

Within a fixed feed supply situation, ewe numbers were very sensitive to changes in livestock production strategies. Strategies that had the greatest improvement in feed conversion efficiency had the greatest impact on the number of ewes able to be carried. A key conclusion is that, unless changes to the livestock system are accompanied by changes to system feed supply, substantial adjustments to breeding ewe numbers may be required. This relationship between livestock strategies and ewe numbers was mostly negative. This has important implications for using livestock numbers or "stocking rate" as the basis of assessing the productive capability of a particular livestock system.

4. Do livestock production parameters that increase biological efficiency also increase economic returns?

It was found that system parameters that had a large impact on biological efficiency did not always have a large impact on economic return. Also, some system livestock parameters that had only a small impact on biological efficiency had a much greater impact on economic return. Therefore, maximisation of biological efficiency will not always result in maximisation of economic returns. Furthermore, in comparison to biological efficiency, which can be characterised by a smooth non-linear response curve, changes in livestock parameters such as lamb carcass weight can result in abrupt and step-wise responses to economic outcomes. A final conclusion is that as the relationship between a particular livestock strategy and whole-of-system gross margin returns were influenced by the feed supply profile, optimal systems will be highly dependent on the specific feed context.

In order to answer the above research questions, the traditional supply-driven modelling approach has been reversed and a new demand-driven approach has been developed. This represents a change in paradigm in livestock modelling and has proved valuable were the focus, rather than being on feed supply, is on the requirements necessary to meet specific animal performance levels and the implications thereof for biological efficiency, seasonality of feed demand and systems economics related to alternative feed supply functions and their associated costs.

Appendix A

Technical Notes

In this technical note, some specific assumptions and implications are discussed and specific details of the model are explained more fully. This technical note is written primarily for future users of the model.

1. Replacement lambs

Theoretically (and practically), replacement ewe lambs can be selected from lambs born to either hoggets, 2-tooth ewes or MA ewes. Indeed, the selection of lambs from younger ewes can help speed up the rate of genetic gain within the flock as a result of decreasing the generation interval. Also, while there are some concerns as to the long-term performance of progeny born to young ewes, Pain, Loureiro, Kenyon, and Blair (2015) reported no significant penalty on reproductive performance by selecting replacement lambs born to hogget dams.

However, in this research it has been assumed that replacement lambs are only selected from singleton or twin ewe lambs born to MA ewes. This simplification has been a consequence of modelling within a deterministic, steady-state framework and 'the curse of dimensionality' (Hardaker et al., 1991). For example, in the model, lambs born to hoggets and 2-tooth ewes each have different birth weights and growth rates and therefore, if replacement lambs are to be selected from progeny born to these dams, their growth profile as hoggets would be different from hoggets selected from lambs born to MA ewes.

2. Misleading nature of percentage changes

When interpreting the results reported in this thesis, it is important to understand the misleading nature of percentage changes. To illustrate, if starting at a value of 1000, a 10% increase followed by a 10% decrease does not result back at the starting value of 1000:

$$1000 \times 1.10 = 1100 \neq 1100 \times 0.90 = 990$$

Rather, the resultant outcome of a percentage change is relative to the input value.

3. Standard Reference Weight

In the base model, as ewe size increased, the energy costs of liveweight gain of growing lambs was reduced. This is because it was assumed that the mature weight of lambs was linked to ewe size. At a given age, lambs with higher mature weights have a lower energy requirement for liveweight gain due to the lower rate of fat deposition (Nicol & Brookes, 2007, p. 156). In a breeding/finishing lamb flock, where replacement lambs are selected from the lambs born, it is expected that the mature liveweight of the lamb is correlated with the mature liveweight of the ewe flock. However, farm managers may use a 'terminal sire' over a proportion of the flock (Kerr, 2010). A terminal sire is a breed of sheep that has been selected specifically for production traits such as lamb growth and are typically much larger in size than maternal type breeds. Therefore, even ignoring the benefit of hybrid vigour and improved lamb growth that can result from this practice, the use of a terminal sire can improve feed conversion efficiency by increasing the mature liveweight of lambs.

Appendix B

Birth Rank Equations[15]

$\mathrm{BR}_1 = -\mathrm{LS} + 2, \qquad \text{for } 1.0 \leq \mathrm{LS} \leq 1.5$

$\mathrm{BR}_1 = -1.1027\mathrm{LS}^4 + 7.7828\mathrm{LS}^3 - 19.7092\mathrm{LS}^2 + 20.5097\mathrm{LS} - 6.6036, \qquad \text{for } 1.5 < \mathrm{LS} \leq 2.2$

$\mathrm{BR}_2 = \mathrm{LS} - 1, \qquad \text{for } 1.0 \leq \mathrm{LS} \leq 1.5$

$\mathrm{BR}_2 = 2.2054\mathrm{LS}^4 - 15.5657\mathrm{LS}^3 + 39.4184\mathrm{LS}^2 - 42.0195\mathrm{LS} + 16.2073, \qquad \text{for } 1.5 < \mathrm{LS} \leq 2.2$

$\mathrm{BR}_3 = 0, \qquad \text{for } 1.0 \leq \mathrm{LS} \leq 1.5$

$\mathrm{BR}_3 = -1.1027\mathrm{LS}^4 + 7.7828\mathrm{LS}^3 - 19.7092\mathrm{LS}^2 + 21.5097\mathrm{LS} - 8.6036, \qquad \text{for } 1.5 < \mathrm{LS} \leq 2.2$

Where:

BR_1 = the proportion of ewes that have single lambs per ewe lambing,

BR_2 = the proportion of ewes that have twin lambs per ewe lambing,

BR_3 = the proportion of ewes that have triplet lambs per ewe lambing, and

LS = is the litter size (number of lambs born per ewe lambing)

[15] For convenience the birth rank equations are presented with 4 d.p. However, in the model, 14 d.p. are used.

Appendix C

Weekly Liveweights

Table C.1 Weekly liveweights of hoggets, ewes, sire rams and replacement ewe lambs

Week starting from ewe mating date	Replacement Lamb		Hogget				2 Tooth Ewe			MA Ewe			Sire Rams
	Single born	Twin born	Unmated	Dry	Single	Twin	Single	Twin	Tiplet	Single	Twin	Tiplet	
1	0.0	0.0	39.2	39.2	39.2	39.2	58.5	58.5	58.5	65.0	65.0	65.0	81.3
2	0.0	0.0	39.6	40.0	40.0	40.0	58.7	58.7	58.7	65.0	65.0	65.0	81.3
3	0.0	0.0	39.9	40.7	40.7	40.7	58.8	58.8	58.8	65.0	65.0	65.0	81.3
4	0.0	0.0	40.3	41.5	41.5	41.5	59.0	59.0	59.0	65.0	65.0	65.0	81.3
5	0.0	0.0	40.7	42.3	42.3	42.3	59.1	59.1	59.1	65.0	65.0	65.0	81.3
6	0.0	0.0	41.0	42.7	42.7	42.7	59.3	59.3	59.3	65.0	65.0	65.0	81.3
7	0.0	0.0	41.4	43.1	43.1	43.1	59.5	59.5	59.5	65.0	65.0	65.0	81.3
8	0.0	0.0	41.8	43.5	43.5	43.5	59.6	59.6	59.6	65.0	65.0	65.0	81.3
9	0.0	0.0	42.2	43.9	43.9	43.9	59.8	59.8	59.8	65.0	65.0	65.0	81.3
10	0.0	0.0	42.5	44.3	44.3	44.3	60.0	60.0	60.0	65.0	65.0	65.0	81.3
11	0.0	0.0	42.8	44.6	44.6	44.6	60.1	60.1	60.1	65.0	65.0	65.0	81.3
12	0.0	0.0	43.3	45.1	45.1	45.1	60.3	60.3	60.3	65.0	65.0	65.0	81.3
13	0.0	0.0	43.6	45.5	45.5	45.5	60.4	60.4	60.4	65.0	65.0	65.0	81.3
14	0.0	0.0	44.0	45.9	45.9	45.9	60.6	60.6	60.6	65.0	65.0	65.0	81.3
15	0.0	0.0	44.4	46.3	46.3	46.3	60.8	60.8	60.8	65.0	65.0	65.0	81.3
16	0.0	0.0	44.8	46.7	46.7	46.7	60.9	60.9	60.9	65.0	65.0	65.0	81.3
17	0.0	0.0	45.1	47.0	47.1	47.1	60.9	60.9	60.9	65.0	65.0	65.0	81.3
18	0.0	0.0	45.5	47.3	47.5	47.5	60.9	60.8	60.7	65.0	64.9	64.8	81.3
19	0.0	0.0	45.9	47.6	47.9	47.9	60.9	60.6	60.5	65.0	64.7	64.5	81.3
20	0.0	0.0	46.2	48.0	48.3	48.3	60.9	60.4	60.1	65.0	64.5	64.2	81.3
21	0.0	0.0	46.6	48.3	48.3	48.3	60.9	60.1	59.6	65.0	64.2	63.7	81.3
22	5.3	4.3	47.0	48.6	48.3	48.3	60.9	59.8	59.0	65.0	63.9	63.1	81.3
23	7.4	6.1	47.4	48.9	48.3	48.2	60.9	59.4	58.3	65.0	63.4	62.4	81.3
24	9.5	7.9	47.7	49.2	48.3	48.1	60.9	58.9	57.5	65.0	63.0	61.6	81.3
25	11.7	9.8	48.1	49.6	48.3	48.0	60.9	58.4	56.8	65.0	62.5	60.9	81.3
26	14.0	11.8	48.5	49.9	48.3	47.9	60.9	58.1	56.3	65.0	62.2	60.4	81.3
27	16.2	13.7	48.8	50.2	48.3	47.8	60.9	58.0	56.0	65.0	62.0	60.1	81.3
28	18.3	15.5	49.2	50.5	48.3	47.6	60.9	57.9	55.9	65.0	62.0	60.0	81.3
29	20.4	17.3	49.6	50.8	48.3	47.5	61.1	58.2	56.3	65.0	62.1	60.2	81.3
30	22.3	19.0	50.0	51.2	48.3	47.4	61.2	58.5	56.6	65.0	62.2	60.4	81.3
31	24.2	20.5	50.3	51.5	48.3	47.3	61.4	58.8	57.0	65.0	62.4	60.6	81.3
32	25.9	22.0	50.7	51.8	48.3	47.3	61.6	59.1	57.4	65.0	62.5	60.8	81.3
33	27.5	23.4	51.1	52.1	48.8	47.8	61.7	59.3	57.7	65.0	62.6	61.0	81.3
34	29.0	24.6	51.4	52.4	49.3	48.4	61.9	59.6	58.1	65.0	62.7	61.2	81.3
35	29.5	25.4	51.8	52.8	49.8	48.9	62.1	59.9	58.5	65.0	62.8	61.4	81.3
36	30.0	26.2	52.2	53.1	50.2	49.4	62.2	60.2	58.8	65.0	63.0	61.6	81.3
37	30.6	26.9	52.6	53.4	50.7	50.0	62.4	60.5	59.2	65.0	63.1	61.8	81.3
38	31.1	27.7	52.9	53.7	51.2	50.5	62.6	60.8	59.6	65.0	63.2	62.0	81.3
39	31.7	28.5	53.3	54.0	51.7	51.0	62.7	61.0	59.9	65.0	63.3	62.2	81.3
40	32.2	29.2	53.7	54.3	52.2	51.6	62.9	61.3	60.3	65.0	63.4	62.4	81.3
41	32.7	30.0	54.0	54.7	52.7	52.1	63.0	61.6	60.6	65.0	63.6	62.6	81.3
42	33.3	30.8	54.4	55.0	53.2	52.6	63.2	61.9	61.0	65.0	63.7	62.8	81.3
43	33.8	31.5	54.8	55.3	53.6	53.2	63.4	62.2	61.4	65.0	63.8	63.0	81.3
44	34.3	32.3	55.2	55.6	54.1	53.7	63.5	62.5	61.7	65.0	63.9	63.2	81.3
45	34.9	33.1	55.5	55.9	54.6	54.2	63.7	62.7	62.1	65.0	64.0	63.4	81.3
46	35.4	33.8	55.9	56.3	55.1	54.8	63.9	63.0	62.5	65.0	64.2	63.6	81.3
47	36.0	34.6	56.3	56.6	55.6	55.3	64.0	63.3	62.8	65.0	64.3	63.8	81.3
48	36.5	35.4	56.6	56.9	56.1	55.8	64.2	63.6	63.2	65.0	64.4	64.0	81.3
49	37.0	36.1	57.0	57.2	56.6	56.4	64.3	63.9	63.5	65.0	64.5	64.2	81.3
50	37.6	36.9	57.4	57.5	57.0	56.9	64.5	64.2	63.9	65.0	64.6	64.4	81.3
51	38.1	37.7	57.8	57.9	57.5	57.4	64.7	64.4	64.3	65.0	64.8	64.6	81.3
52	38.7	38.4	58.1	58.2	58.0	58.0	64.8	64.7	64.6	65.0	64.9	64.8	81.3

Table C.2 Weekly Liveweights of sale lambs (kg)

Week starting from ewe mating date	Hogget Dam								Two-Tooth Dam																Mixed-Aged Ewe Dam															
	Single				Twin				Single				Twin				Triplet				Single				Twin				Triplet			
	Ewe		Ram		Ewe		Ram		Ewe		Ram		Ewe		Ram		Ewe		Ram		Ewe		Ram		Ewe		Ram		Ewe		Ram	
	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2	Yr1	Yr2
1						37.8																										
2						39.0																										
3																																
4																																
5																																
6																																
7																																
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17																																
18																																
19																																
20																																
21																																
22									5.3		5.7		4.3		4.5		3.8		4.0		5.3		5.7		4.3		4.5		3.8		4.0	
23									7.2		7.9		5.9		6.4		5.2		5.6		7.4		8.0		6.1		6.5		5.3		5.7	
24									9.2		10.1		7.7		8.3		6.7		7.3		9.5		10.4		7.9		8.6		6.9		7.6	
25									11.3		12.5		9.4		10.3		8.3		9.1		11.7		13.0		9.8		10.7		8.6		9.4	
26	4.3		4.7		3.5		3.7		13.4		14.8		11.2		12.3		9.8		10.8		14.0		15.5		11.8		12.9		10.3		11.3	
27	6.0		6.6		5.0		5.3		15.4		17.1		13.0		14.3		11.4		12.6		16.2		18.0		13.7		15.1		11.9		13.2	
28	7.8		8.6		6.5		7.1		17.4		19.4		14.7		16.3		12.9		14.2		18.3		20.4		15.5		17.2		13.6		15.0	
29	9.6		10.7		8.1		8.9		19.3		21.6		16.4		18.1		14.3		15.9		20.4		22.7		17.3		19.2		15.1		16.8	
30	11.5		12.8		9.7		10.7		21.1		23.6		17.9		19.9		15.7		17.4		22.3		25.0		19.0		21.1		16.5		18.4	
31	13.3		14.8		11.2		12.4		22.8		25.5		19.4		21.6		16.9		18.8		24.2		27.0		20.5		22.8		17.9		20.0	
32	15.0		16.8		12.7		14.1		24.4		27.3		20.8		23.1		18.1		20.2		25.9		29.0		22.0		24.5		19.2		21.4	
33	16.7		18.7		14.2		15.8		25.9		29.0		22.0		24.5		19.2		21.4		27.5		30.8		23.4		26.1		20.4		22.8	
34	18.3		20.6		15.6		17.3		27.3		30.6		23.2		25.9		20.3		22.6		29.0		32.4		24.6		27.5		21.5		24.0	
35	19.9		22.3		16.9		18.8		28.6		32.0		24.4		27.2		21.4		23.9		30.3		33.9		25.9		28.9		22.7		25.3	
36	21.3		23.9		18.1		20.2		29.8		33.4		25.5		28.5		22.5		25.1		31.6		35.4		27.1		30.3		23.8		26.6	
37	22.5		25.3		19.2		21.5		31.1		34.8		26.7		29.8		23.6		26.3		32.9		36.9		28.3		31.6		25.0		27.9	
38	23.8		26.7		20.4		22.8		32.3		36.2		27.9		31.1		24.7		27.6		34.2		38.4		29.5		33.0		26.1		29.3	
39	25.0		28.1		21.6		24.1		33.5		37.6		29.0		32.4		25.8		28.8		35.5		39.9		30.8		34.4		27.3		30.6	
40	26.3		29.5		22.7		25.4		34.8		39.0		30.2		33.8		26.9		30.1		36.8		41.4		32.0		35.8		28.5		31.9	
41	27.5		30.9		23.9		26.7		36.0		40.4		31.4		35.1		28.0		31.3		38.2				33.2		37.2		29.6		33.2	
42	28.8		32.3		25.1		28.1		37.3				32.5		36.4		29.1		32.6		39.5				34.4		38.5		30.8		34.5	
43	30.0		33.7		26.2		29.4		38.5				33.7		37.7		30.2		33.8						35.7		39.9		32.0		35.8	
44	31.2		35.2		27.4		30.7						34.8		39.0		31.3		35.1						36.9		41.3		33.1		37.1	
45	32.5		36.6		28.5		32.0						36.0		40.3		32.4		36.3						38.1				34.3		38.4	
46	33.7		38.0		29.7		33.3						37.2				33.5		37.6						39.3				35.4		39.8	
47	35.0		39.4		30.9		34.6						38.3				34.6		38.8										36.6		41.1	
48	36.2		40.8		32.0		35.9						39.5				35.7		40.1										37.8			
49	37.5				33.2		37.2										36.8		41.3										38.9			
50	38.7				34.3		38.6										37.9															
51					35.5		39.9										39.0															
52					36.7		41.2																									

Appendix D

Baseline Energy Requirements

Table D.1 Weekly energy requirements (MJME/hd/day) for maintenance (ME m) and liveweight gain (ME g) of an unmated hogget

Week starting from ewe mating date	ME m (hogget)	ME g (hogget)	Total MJME
1	7.4	2.7	10.1
2	7.5	2.7	10.2
3	7.5	2.7	10.2
4	7.6	2.7	10.3
5	7.6	2.7	10.4
6	7.7	2.8	10.4
7	7.8	2.8	10.5
8	7.8	2.8	10.6
9	7.9	2.8	10.7
10	7.9	2.8	10.7
11	8.0	2.8	10.8
12	8.0	2.8	10.9
13	8.1	2.8	10.9
14	8.1	2.9	11.0
15	8.2	2.9	11.1
16	8.2	2.9	11.1
17	8.3	2.9	11.2
18	8.4	2.9	11.2
19	8.4	2.9	11.3
20	8.5	2.9	11.4
21	8.5	2.9	11.4
22	8.6	2.9	11.5
23	8.6	2.9	11.6
24	8.7	3.0	11.6
25	8.7	3.0	11.7
26	8.6	2.8	11.5
27	8.7	2.8	11.5
28	8.7	2.9	11.6
29	8.8	2.9	11.6
30	8.8	2.9	11.7
31	8.9	2.9	11.8
32	8.9	2.9	11.8
33	9.0	2.9	11.9
34	9.0	2.9	11.9
35	9.1	2.9	12.0
36	9.3	3.0	12.4
37	9.4	3.0	12.4
38	9.4	3.1	12.5
39	9.5	3.1	12.5
40	9.5	3.1	12.6
41	9.6	3.1	12.7
42	9.6	3.1	12.7
43	9.7	3.1	12.8
44	9.7	3.1	12.8
45	9.8	3.1	12.9
46	9.8	3.1	12.9
47	9.9	3.1	13.0
48	9.9	3.1	13.1
49	10.0	3.1	13.1
50	10.1	3.1	13.2
51	10.1	3.1	13.2
52	10.2	3.1	13.3
Annual Total	3192.5	1063.5	4256.0

Table D.2 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a hogget with a single ewe lamb

Week starting from ewe mating date	ME m (hogget)	ME g (hogget)	ME p (hogget)	ME l (lamb)	ME m (lamb)	ME g (lamb)	Total MJME for hogget & lamb
1	7.4	0.0	5.3	0.0	0.0	0.0	12.7
2	7.5	0.0	5.4	0.0	0.0	0.0	12.9
3	7.6	0.0	5.4	0.0	0.0	0.0	13.1
4	7.7	0.0	5.5	0.0	0.0	0.0	13.2
5	7.8	0.0	2.9	0.0	0.0	0.0	10.7
6	7.9	0.0	2.9	0.0	0.0	0.0	10.8
7	7.9	0.0	2.9	0.0	0.0	0.0	10.9
8	8.0	0.1	2.9	0.0	0.0	0.0	11.0
9	8.1	0.1	3.0	0.0	0.0	0.0	11.1
10	8.1	0.1	3.0	0.0	0.0	0.0	11.2
11	8.2	0.2	3.0	0.0	0.0	0.0	11.4
12	8.2	0.3	3.0	0.0	0.0	0.0	11.5
13	8.3	0.4	3.0	0.0	0.0	0.0	11.7
14	8.4	0.5	3.0	0.0	0.0	0.0	11.9
15	8.4	0.7	3.0	0.0	0.0	0.0	12.1
16	8.5	0.9	3.0	0.0	0.0	0.0	12.4
17	8.5	1.1	3.0	0.0	0.0	0.0	12.7
18	8.6	1.4	3.1	0.0	0.0	0.0	13.1
19	8.7	1.8	3.1	0.0	0.0	0.0	13.5
20	8.7	2.2	0.0	0.0	0.0	0.0	10.9
21	8.7	2.7	0.0	0.0	0.0	0.0	11.4
22	8.7	3.3	0.0	0.0	0.0	0.0	12.0
23	8.7	3.9	0.0	0.0	0.0	0.0	12.6
24	8.7	4.7	0.0	0.0	0.0	0.0	13.4
25	8.7	5.5	0.0	0.0	0.0	0.0	14.2
26	8.7	0.0	0.0	8.5	0.0	0.0	17.1
27	8.7	0.0	0.0	9.6	0.0	0.0	18.3
28	8.7	0.0	0.0	10.6	0.0	0.0	19.3
29	8.7	0.0	0.0	11.6	0.0	0.0	20.2
30	8.7	0.0	0.0	12.1	0.0	0.0	20.8
31	8.7	0.0	0.0	12.5	0.0	0.0	21.2
32	8.7	0.0	3.7	12.8	0.0	0.0	25.2
33	8.8	0.0	3.7	12.9	0.0	0.0	25.4
34	8.9	0.0	3.7	12.9	0.0	0.0	25.5
35	8.9	0.0	3.7	12.8	0.0	0.0	25.5
36	9.0	0.0	3.8	0.0	4.6	5.9	23.2
37	9.1	0.0	3.8	0.0	4.8	6.1	23.7
38	9.1	0.0	3.8	0.0	5.0	6.4	24.2
39	9.2	0.0	3.8	0.0	5.2	6.6	24.7
40	9.3	0.0	3.8	0.0	5.4	6.8	25.2
41	9.3	0.0	3.8	0.0	5.6	7.0	25.7
42	9.4	0.0	3.8	0.0	5.8	7.2	26.2
43	9.5	0.0	3.8	0.0	5.9	7.4	26.7
44	9.5	0.0	3.8	0.0	6.1	7.6	27.2
45	9.6	0.0	3.8	0.0	6.3	7.8	27.6
46	9.7	0.0	3.9	0.0	6.5	8.0	28.1
47	9.8	0.0	3.9	0.0	6.7	8.2	28.5
48	9.8	0.0	3.9	0.0	6.9	8.4	29.0
49	9.9	0.0	3.9	0.0	7.1	8.6	29.4
50	10.0	0.0	3.9	0.0	5.2	6.2	25.2
51	10.0	0.0	3.9	0.0	0.0	0.0	13.9
52	10.1	0.0	3.9	0.0	0.0	0.0	14.0
Annual Total	3190.0	208.9	1025.8	813.7	608.5	758.0	6604.9

Table D.3 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a hogget with a single ram lamb

Week starting from ewe mating date	ME m (hogget)	ME g (hogget)	ME p (hogget)	ME l (lamb)	ME m (lamb)	ME g (lamb)	Total MJME for hogget & lamb
1	7.4	0.0	5.3	0.0	0.0	0.0	12.7
2	7.5	0.0	5.4	0.0	0.0	0.0	12.9
3	7.6	0.0	5.4	0.0	0.0	0.0	13.1
4	7.7	0.0	5.5	0.0	0.0	0.0	13.2
5	7.8	0.0	2.9	0.0	0.0	0.0	10.7
6	7.9	0.0	2.9	0.0	0.0	0.0	10.8
7	7.9	0.0	2.9	0.0	0.0	0.0	10.9
8	8.0	0.1	2.9	0.0	0.0	0.0	11.0
9	8.1	0.1	3.0	0.0	0.0	0.0	11.1
10	8.1	0.1	3.0	0.0	0.0	0.0	11.2
11	8.2	0.2	3.0	0.0	0.0	0.0	11.4
12	8.2	0.3	3.0	0.0	0.0	0.0	11.5
13	8.3	0.4	3.0	0.0	0.0	0.0	11.7
14	8.4	0.5	3.0	0.0	0.0	0.0	11.9
15	8.4	0.7	3.0	0.0	0.0	0.0	12.1
16	8.5	0.9	3.0	0.0	0.0	0.0	12.4
17	8.5	1.1	3.0	0.0	0.0	0.0	12.7
18	8.6	1.4	3.1	0.0	0.0	0.0	13.1
19	8.7	1.8	3.1	0.0	0.0	0.0	13.5
20	8.7	2.2	0.0	0.0	0.0	0.0	10.9
21	8.7	2.7	0.0	0.0	0.0	0.0	11.4
22	8.7	3.3	0.0	0.0	0.0	0.0	12.0
23	8.7	3.9	0.0	0.0	0.0	0.0	12.6
24	8.7	4.7	0.0	0.0	0.0	0.0	13.4
25	8.7	5.5	0.0	0.0	0.0	0.0	14.2
26	8.7	0.0	0.0	9.6	0.0	0.0	18.3
27	8.7	0.0	0.0	10.9	0.0	0.0	19.6
28	8.7	0.0	0.0	12.1	0.0	0.0	20.8
29	8.7	0.0	0.0	13.1	0.0	0.0	21.8
30	8.7	0.0	0.0	13.7	0.0	0.0	22.4
31	8.7	0.0	0.0	14.2	0.0	0.0	22.9
32	8.7	0.0	3.7	14.5	0.0	0.0	26.9
33	8.8	0.0	3.7	14.7	0.0	0.0	27.2
34	8.9	0.0	3.7	14.7	0.0	0.0	27.3
35	8.9	0.0	3.7	14.6	0.0	0.0	27.3
36	9.0	0.0	3.8	0.0	5.6	6.3	24.6
37	9.1	0.0	3.8	0.0	5.9	6.5	25.2
38	9.1	0.0	3.8	0.0	6.1	6.7	25.7
39	9.2	0.0	3.8	0.0	6.4	6.9	26.3
40	9.3	0.0	3.8	0.0	6.6	7.1	26.8
41	9.3	0.0	3.8	0.0	6.9	7.3	27.4
42	9.4	0.0	3.8	0.0	7.1	7.6	27.9
43	9.5	0.0	3.8	0.0	7.3	7.8	28.4
44	9.5	0.0	3.8	0.0	7.6	8.0	29.0
45	9.6	0.0	3.8	0.0	7.8	8.2	29.5
46	9.7	0.0	3.9	0.0	8.0	8.4	30.0
47	9.8	0.0	3.9	0.0	8.3	8.7	30.5
48	9.8	0.0	3.9	0.0	6.1	6.3	26.0
49	9.9	0.0	3.9	0.0	0.0	0.0	13.8
50	10.0	0.0	3.9	0.0	0.0	0.0	13.8
51	10.0	0.0	3.9	0.0	0.0	0.0	13.9
52	10.1	0.0	3.9	0.0	0.0	0.0	14.0
Annual Total	3190.0	208.9	1025.8	925.1	627.3	670.7	6647.8

Table D.4 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a hogget with twin ewe lambs

Week starting from ewe mating date	ME m (hogget)	ME g (hogget)	ME p (hogget)	ME l (per lamb)	ME l (twin lambs)	ME m (per lamb)	ME m (twin lambs)	ME g (per lamb)	ME g (twin lambs)	Total MJME for hogget & lambs
1	7.5	5.3	0.0	0.0	0.0	7.3	14.5	8.4	16.7	44.0
2	7.6	5.4	0.0	0.0	0.0	4.2	8.5	4.8	9.7	31.1
3	7.7	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.1
4	7.8	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.3
5	7.9	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.8
6	8.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9
7	8.0	2.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.0
8	8.1	2.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.1
9	8.1	3.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	11.2
10	8.2	3.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	11.4
11	8.2	3.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	11.5
12	8.3	3.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	11.7
13	8.4	3.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	12.0
14	8.4	3.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	12.2
15	8.5	3.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	12.6
16	8.5	3.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	13.0
17	8.6	3.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	13.4
18	8.7	3.1	2.3	0.0	0.0	0.0	0.0	0.0	0.0	14.0
19	8.7	3.1	2.8	0.0	0.0	0.0	0.0	0.0	0.0	14.6
20	8.8	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	12.2
21	8.8	-0.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0	12.9
22	8.7	-0.2	5.2	0.0	0.0	0.0	0.0	0.0	0.0	13.8
23	8.7	-0.3	6.3	0.0	0.0	0.0	0.0	0.0	0.0	14.7
24	8.7	-0.4	7.5	0.0	0.0	0.0	0.0	0.0	0.0	15.8
25	8.7	-0.5	8.8	0.0	0.0	0.0	0.0	0.0	0.0	17.0
26	8.7	-0.6	0.0	7.0	14.0	0.0	0.0	0.0	0.0	22.1
27	8.7	-0.7	0.0	8.0	16.0	0.0	0.0	0.0	0.0	23.9
28	8.6	-0.6	0.0	8.8	17.7	0.0	0.0	0.0	0.0	25.7
29	8.6	-0.4	0.0	9.4	18.9	0.0	0.0	0.0	0.0	27.1
30	8.6	-0.2	0.0	9.8	19.7	0.0	0.0	0.0	0.0	28.1
31	8.6	-0.1	0.0	10.1	20.3	0.0	0.0	0.0	0.0	28.8
32	8.6	4.0	0.0	10.3	20.7	0.0	0.0	0.0	0.0	33.4
33	8.7	4.1	0.0	10.4	20.8	0.0	0.0	0.0	0.0	33.6
34	8.8	4.1	0.0	10.3	20.6	0.0	0.0	0.0	0.0	33.5
35	8.9	4.1	0.0	10.1	20.2	0.0	0.0	0.0	0.0	33.1
36	9.0	4.1	0.0	0.0	0.0	4.0	8.0	5.0	10.0	31.1
37	9.0	4.1	0.0	0.0	0.0	4.2	8.4	5.2	10.4	31.9
38	9.1	4.1	0.0	0.0	0.0	4.4	8.8	5.4	10.7	32.8
39	9.2	4.1	0.0	0.0	0.0	4.6	9.2	5.5	11.1	33.6
40	9.3	4.2	0.0	0.0	0.0	4.8	9.6	5.7	11.4	34.4
41	9.3	4.2	0.0	0.0	0.0	5.0	10.0	5.9	11.8	35.3
42	9.4	4.2	0.0	0.0	0.0	5.2	10.3	6.1	12.2	36.1
43	9.5	4.2	0.0	0.0	0.0	5.4	10.7	6.3	12.6	37.0
44	9.6	4.2	0.0	0.0	0.0	5.5	11.1	6.5	12.9	37.8
45	9.6	4.2	0.0	0.0	0.0	5.7	11.4	6.7	13.3	38.6
46	9.7	4.2	0.0	0.0	0.0	5.9	11.8	6.8	13.7	39.4
47	9.8	4.2	0.0	0.0	0.0	6.1	12.2	7.0	14.0	40.2
48	9.9	4.2	0.0	0.0	0.0	6.3	12.5	7.2	14.4	41.0
49	9.9	4.3	0.0	0.0	0.0	6.4	12.9	7.4	14.7	41.8
50	10.0	4.3	0.0	0.0	0.0	6.6	13.2	7.5	15.1	42.6
51	10.1	4.3	0.0	0.0	0.0	6.8	13.6	7.7	15.4	43.3
52	10.2	4.3	0.0	0.0	0.0	7.0	13.9	7.8	15.7	44.0
Annual Total	3199.2	1049.0	334.3	660.8	1321.7	736.9	1473.8	859.8	1719.6	9097.6

Table D.5 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a hogget with twin ram lambs

Week starting from ewe mating date	ME m (hogget)	ME g (hogget)	ME p (hogget)	ME l (per lamb)	ME l (twin lambs)	ME m (per lamb)	ME m (twin lambs)	ME g (per lamb)	ME g (twin lambs)	Total MJME for hogget & lambs
1	7.5	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	12.8
2	7.6	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	12.9
3	7.7	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	13.1
4	7.8	0.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0	13.3
5	7.9	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	10.8
6	8.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	10.9
7	8.0	0.1	2.9	0.0	0.0	0.0	0.0	0.0	0.0	11.0
8	8.1	0.1	2.9	0.0	0.0	0.0	0.0	0.0	0.0	11.1
9	8.1	0.2	3.0	0.0	0.0	0.0	0.0	0.0	0.0	11.2
10	8.2	0.2	3.0	0.0	0.0	0.0	0.0	0.0	0.0	11.4
11	8.2	0.3	3.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
12	8.3	0.4	3.0	0.0	0.0	0.0	0.0	0.0	0.0	11.7
13	8.4	0.6	3.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0
14	8.4	0.8	3.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
15	8.5	1.1	3.0	0.0	0.0	0.0	0.0	0.0	0.0	12.6
16	8.5	1.4	3.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0
17	8.6	1.8	3.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4
18	8.7	2.3	3.1	0.0	0.0	0.0	0.0	0.0	0.0	14.0
19	8.7	2.8	3.1	0.0	0.0	0.0	0.0	0.0	0.0	14.6
20	8.8	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
21	8.8	4.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	12.9
22	8.7	5.2	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	13.8
23	8.7	6.3	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	14.7
24	8.7	7.5	-0.4	0.0	0.0	0.0	0.0	0.0	0.0	15.8
25	8.7	8.8	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	17.0
26	8.7	0.0	-0.6	7.9	0.0	0.0	15.9	0.0	0.0	24.0
27	8.7	0.0	-0.7	9.0	0.0	0.0	18.1	0.0	0.0	26.1
28	8.6	0.0	-0.6	10.0	0.0	0.0	20.1	0.0	0.0	28.1
29	8.6	0.0	-0.4	10.7	0.0	0.0	21.5	0.0	0.0	29.7
30	8.6	0.0	-0.2	11.2	0.0	0.0	22.4	0.0	0.0	30.8
31	8.6	0.0	-0.1	11.6	0.0	0.0	23.1	0.0	0.0	31.7
32	8.6	0.0	4.0	11.8	0.0	0.0	23.6	0.0	0.0	36.3
33	8.7	0.0	4.1	11.9	0.0	0.0	23.8	0.0	0.0	36.6
34	8.8	0.0	4.1	11.7	0.0	0.0	23.5	0.0	0.0	36.4
35	8.9	0.0	4.1	11.5	0.0	0.0	23.0	0.0	0.0	35.9
36	9.0	0.0	4.1	0.0	4.9	5.3	0.0	9.9	10.6	33.6
37	9.0	0.0	4.1	0.0	5.2	5.5	0.0	10.3	11.0	34.5
38	9.1	0.0	4.1	0.0	5.4	5.7	0.0	10.8	11.3	35.4
39	9.2	0.0	4.1	0.0	5.7	5.8	0.0	11.3	11.7	36.3
40	9.3	0.0	4.2	0.0	5.9	6.0	0.0	11.8	12.0	37.2
41	9.3	0.0	4.2	0.0	6.1	6.2	0.0	12.2	12.4	38.1
42	9.4	0.0	4.2	0.0	6.4	6.4	0.0	12.7	12.8	39.1
43	9.5	0.0	4.2	0.0	6.6	6.6	0.0	13.2	13.1	40.0
44	9.6	0.0	4.2	0.0	6.8	6.8	0.0	13.6	13.5	40.9
45	9.6	0.0	4.2	0.0	7.0	7.0	0.0	14.1	13.9	41.8
46	9.7	0.0	4.2	0.0	7.3	7.2	0.0	14.5	14.3	42.8
47	9.8	0.0	4.2	0.0	7.5	7.3	0.0	15.0	14.7	43.7
48	9.9	0.0	4.2	0.0	7.7	7.5	0.0	15.4	15.1	44.6
49	9.9	0.0	4.3	0.0	7.9	7.7	0.0	15.8	15.4	45.5
50	10.0	0.0	4.3	0.0	8.1	7.9	0.0	16.3	15.8	46.4
51	10.1	0.0	4.3	0.0	8.3	8.1	0.0	16.7	16.2	47.2
52	10.2	0.0	4.3	0.0	3.6	3.5	0.0	7.3	7.0	28.8
Annual Total	3199.2	334.3	1049.0	752.0	772.8	773.1	1503.9	1545.7	1546.2	9178.4

Table D.6 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a 2-tooth ewe with a single ewe lamb

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (lamb)	ME m (lamb)	ME g (lamb)	Total MJME for ewe & lamb
1	10.1	1.4	0.0	0.0	0.0	0.0	11.5
2	10.1	1.4	0.0	0.0	0.0	0.0	11.5
3	10.2	1.4	0.1	0.0	0.0	0.0	11.6
4	10.2	1.4	0.1	0.0	0.0	0.0	11.6
5	10.2	1.4	0.1	0.0	0.0	0.0	11.7
6	10.2	1.4	0.2	0.0	0.0	0.0	11.8
7	10.3	1.4	0.2	0.0	0.0	0.0	11.9
8	10.3	1.4	0.3	0.0	0.0	0.0	12.0
9	10.3	1.4	0.4	0.0	0.0	0.0	12.1
10	10.3	1.4	0.6	0.0	0.0	0.0	12.3
11	10.3	1.4	0.8	0.0	0.0	0.0	12.5
12	10.4	1.4	1.0	0.0	0.0	0.0	12.8
13	10.4	1.4	1.4	0.0	0.0	0.0	13.1
14	10.4	1.4	1.7	0.0	0.0	0.0	13.5
15	10.4	1.4	2.2	0.0	0.0	0.0	14.0
16	10.5	0.0	2.7	0.0	0.0	0.0	13.1
17	10.5	0.0	3.3	0.0	0.0	0.0	13.8
18	10.5	0.0	4.0	0.0	0.0	0.0	14.5
19	10.5	0.0	4.8	0.0	0.0	0.0	15.3
20	10.5	0.0	5.7	0.0	0.0	0.0	16.2
21	10.5	0.0	6.8	0.0	0.0	0.0	17.2
22	10.2	0.0	0.0	10.0	0.0	0.0	20.2
23	10.2	0.0	0.0	11.3	0.0	0.0	21.5
24	10.2	0.0	0.0	12.6	0.0	0.0	22.8
25	10.2	0.0	0.0	13.7	0.0	0.0	23.9
26	10.2	0.0	0.0	14.4	0.0	0.0	24.6
27	10.2	0.0	0.0	14.9	0.0	0.0	25.1
28	10.2	1.3	0.0	15.1	0.0	0.0	26.7
29	10.3	1.3	0.0	15.3	0.0	0.0	26.9
30	10.3	1.3	0.0	15.4	0.0	0.0	27.0
31	10.3	1.3	0.0	15.3	0.0	0.0	26.9
32	10.3	1.3	0.0	15.0	0.0	0.0	26.7
33	10.3	1.3	0.0	14.6	0.0	0.0	26.2
34	10.6	1.4	0.0	0.0	5.5	7.0	24.5
35	10.6	1.4	0.0	0.0	5.7	7.2	24.9
36	10.6	1.4	0.0	0.0	5.9	7.4	25.3
37	10.7	1.4	0.0	0.0	6.1	7.6	25.8
38	10.7	1.4	0.0	0.0	6.3	7.8	26.2
39	10.7	1.4	0.0	0.0	6.5	8.0	26.6
40	10.7	1.4	0.0	0.0	6.7	8.2	27.0
41	10.8	1.4	0.0	0.0	6.9	8.4	27.4
42	10.8	1.4	0.0	0.0	7.1	8.5	27.7
43	10.8	1.4	0.0	0.0	6.2	7.4	25.8
44	10.8	1.4	0.0	0.0	0.0	0.0	12.2
45	10.8	1.4	0.0	0.0	0.0	0.0	12.2
46	10.9	1.4	0.0	0.0	0.0	0.0	12.3
47	10.9	1.4	0.0	0.0	0.0	0.0	12.3
48	10.9	1.4	0.0	0.0	0.0	0.0	12.3
49	10.9	1.4	0.0	0.0	0.0	0.0	12.3
50	11.0	1.4	0.0	0.0	0.0	0.0	12.3
51	11.0	1.4	0.0	0.0	0.0	0.0	12.4
52	11.0	1.4	0.0	0.0	0.0	0.0	12.4
Annual Total	3815.7	383.5	255.4	1173.3	440.2	542.2	6610.2

Table D.7 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a 2-tooth ewe with a single ram lamb

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (lamb)	ME m (lamb)	ME g (lamb)	Total MJME for ewe & lamb
1	10.1	1.4	0.0	0.0	0.0	0.0	11.5
2	10.1	1.4	0.0	0.0	0.0	0.0	11.5
3	10.2	1.4	0.1	0.0	0.0	0.0	11.6
4	10.2	1.4	0.1	0.0	0.0	0.0	11.6
5	10.2	1.4	0.1	0.0	0.0	0.0	11.7
6	10.2	1.4	0.2	0.0	0.0	0.0	11.8
7	10.3	1.4	0.2	0.0	0.0	0.0	11.9
8	10.3	1.4	0.3	0.0	0.0	0.0	12.0
9	10.3	1.4	0.4	0.0	0.0	0.0	12.1
10	10.3	1.4	0.6	0.0	0.0	0.0	12.3
11	10.3	1.4	0.8	0.0	0.0	0.0	12.5
12	10.4	1.4	1.0	0.0	0.0	0.0	12.8
13	10.4	1.4	1.4	0.0	0.0	0.0	13.1
14	10.4	1.4	1.7	0.0	0.0	0.0	13.5
15	10.4	1.4	2.2	0.0	0.0	0.0	14.0
16	10.5	0.0	2.7	0.0	0.0	0.0	13.1
17	10.5	0.0	3.3	0.0	0.0	0.0	13.8
18	10.5	0.0	4.0	0.0	0.0	0.0	14.5
19	10.5	0.0	4.8	0.0	0.0	0.0	15.3
20	10.5	0.0	5.7	0.0	0.0	0.0	16.2
21	10.5	0.0	6.8	0.0	0.0	0.0	17.2
22	10.2	0.0	0.0	11.3	0.0	0.0	21.5
23	10.2	0.0	0.0	12.8	0.0	0.0	23.0
24	10.2	0.0	0.0	14.2	0.0	0.0	24.5
25	10.2	0.0	0.0	15.5	0.0	0.0	25.7
26	10.2	0.0	0.0	16.2	0.0	0.0	26.4
27	10.2	0.0	0.0	16.8	0.0	0.0	27.0
28	10.2	1.3	0.0	17.1	0.0	0.0	28.6
29	10.3	1.3	0.0	17.3	0.0	0.0	28.9
30	10.3	1.3	0.0	17.3	0.0	0.0	28.9
31	10.3	1.3	0.0	17.2	0.0	0.0	28.9
32	10.3	1.3	0.0	16.9	0.0	0.0	28.5
33	10.3	1.3	0.0	16.4	0.0	0.0	28.1
34	10.6	1.4	0.0	0.0	6.8	7.3	26.1
35	10.6	1.4	0.0	0.0	7.0	7.5	26.6
36	10.6	1.4	0.0	0.0	7.3	7.7	27.0
37	10.7	1.4	0.0	0.0	7.5	8.0	27.5
38	10.7	1.4	0.0	0.0	7.7	8.2	28.0
39	10.7	1.4	0.0	0.0	8.0	8.4	28.5
40	10.7	1.4	0.0	0.0	8.2	8.6	28.9
41	10.8	1.4	0.0	0.0	7.2	7.5	26.9
42	10.8	1.4	0.0	0.0	0.0	0.0	12.2
43	10.8	1.4	0.0	0.0	0.0	0.0	12.2
44	10.8	1.4	0.0	0.0	0.0	0.0	12.2
45	10.8	1.4	0.0	0.0	0.0	0.0	12.2
46	10.9	1.4	0.0	0.0	0.0	0.0	12.3
47	10.9	1.4	0.0	0.0	0.0	0.0	12.3
48	10.9	1.4	0.0	0.0	0.0	0.0	12.3
49	10.9	1.4	0.0	0.0	0.0	0.0	12.3
50	11.0	1.4	0.0	0.0	0.0	0.0	12.3
51	11.0	1.4	0.0	0.0	0.0	0.0	12.4
52	11.0	1.4	0.0	0.0	0.0	0.0	12.4
Annual Total	3815.7	383.5	255.4	1322.0	418.6	442.4	6637.6

Table D.8 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a 2-tooth ewe with twin ewe lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (twin lambs)	ME m (per lamb)	ME m (twin lambs)	ME g (per lamb)	ME g (twin lambs)	Total MJME for ewe & lambs
1	10.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
2	10.2	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.7
3	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.7
4	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.8
5	10.3	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	11.9
6	10.3	1.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	12.0
7	10.4	1.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	12.1
8	10.4	1.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	12.3
9	10.4	1.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	12.5
10	10.4	1.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8
11	10.5	1.4	1.3	0.0	0.0	0.0	0.0	0.0	0.0	13.1
12	10.5	1.4	1.7	0.0	0.0	0.0	0.0	0.0	0.0	13.5
13	10.5	1.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	14.0
14	10.5	1.4	2.8	0.0	0.0	0.0	0.0	0.0	0.0	14.6
15	10.5	1.4	3.5	0.0	0.0	0.0	0.0	0.0	0.0	15.4
16	10.6	-0.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0	14.7
17	10.5	-0.4	5.3	0.0	0.0	0.0	0.0	0.0	0.0	15.4
18	10.5	-0.7	6.4	0.0	0.0	0.0	0.0	0.0	0.0	16.3
19	10.5	-1.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	17.2
20	10.5	-1.2	9.2	0.0	0.0	0.0	0.0	0.0	0.0	18.4
21	10.4	-1.5	10.8	0.0	0.0	0.0	0.0	0.0	0.0	19.7
22	10.1	-1.8	0.0	8.2	16.5	0.0	0.0	0.0	0.0	24.8
23	10.1	-2.1	0.0	9.3	18.7	0.0	0.0	0.0	0.0	26.6
24	10.0	-1.9	0.0	10.4	20.8	0.0	0.0	0.0	0.0	28.9
25	9.9	-1.3	0.0	11.1	22.2	0.0	0.0	0.0	0.0	30.9
26	9.9	-0.7	0.0	11.6	23.2	0.0	0.0	0.0	0.0	32.4
27	9.9	-0.2	0.0	12.0	23.9	0.0	0.0	0.0	0.0	33.7
28	9.9	2.3	0.0	12.1	24.3	0.0	0.0	0.0	0.0	36.5
29	10.0	2.3	0.0	12.3	24.5	0.0	0.0	0.0	0.0	36.7
30	10.0	2.3	0.0	12.2	24.4	0.0	0.0	0.0	0.0	36.7
31	10.0	2.3	0.0	11.9	23.9	0.0	0.0	0.0	0.0	36.2
32	10.1	2.3	0.0	11.6	23.2	0.0	0.0	0.0	0.0	35.6
33	10.1	2.3	0.0	11.2	22.5	0.0	0.0	0.0	0.0	34.8
34	10.4	2.4	0.0	0.0	0.0	4.9	9.7	5.8	11.6	34.1
35	10.4	2.4	0.0	0.0	0.0	5.1	10.1	6.0	12.0	34.9
36	10.5	2.4	0.0	0.0	0.0	5.2	10.5	6.2	12.3	35.7
37	10.5	2.4	0.0	0.0	0.0	5.4	10.9	6.4	12.7	36.5
38	10.5	2.4	0.0	0.0	0.0	5.6	11.2	6.5	13.1	37.3
39	10.6	2.4	0.0	0.0	0.0	5.8	11.6	6.7	13.5	38.0
40	10.6	2.4	0.0	0.0	0.0	6.0	11.9	6.9	13.8	38.8
41	10.7	2.4	0.0	0.0	0.0	6.2	12.3	7.1	14.2	39.6
42	10.7	2.4	0.0	0.0	0.0	6.3	12.7	7.3	14.5	40.3
43	10.7	2.4	0.0	0.0	0.0	6.5	13.0	7.4	14.9	41.0
44	10.8	2.4	0.0	0.0	0.0	6.7	13.4	7.6	15.2	41.8
45	10.8	2.4	0.0	0.0	0.0	6.9	13.7	7.7	15.5	42.4
46	10.9	2.4	0.0	0.0	0.0	7.0	14.1	7.9	15.8	43.1
47	10.9	2.4	0.0	0.0	0.0	7.2	14.4	8.0	16.1	43.8
48	10.9	2.4	0.0	0.0	0.0	1.0	2.1	1.2	2.3	17.8
49	11.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4
50	11.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4
51	11.1	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.5
52	11.1	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.5
Annual Total	3800.9	468.8	408.6	937.9	1875.9	600.5	1201.0	691.2	1382.4	9137.5

Table D.9 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a 2-tooth ewe with twin ram lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (twin lambs)	ME m (per lamb)	ME m (twin lambs)	ME g (per lamb)	ME g (twin lambs)	Total MJME for ewe & lambs
1	10.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
2	10.2	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.7
3	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.7
4	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.8
5	10.3	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	11.9
6	10.3	1.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	12.0
7	10.4	1.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	12.1
8	10.4	1.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	12.3
9	10.4	1.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	12.5
10	10.4	1.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8
11	10.5	1.4	1.3	0.0	0.0	0.0	0.0	0.0	0.0	13.1
12	10.5	1.4	1.7	0.0	0.0	0.0	0.0	0.0	0.0	13.5
13	10.5	1.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	14.0
14	10.5	1.4	2.8	0.0	0.0	0.0	0.0	0.0	0.0	14.6
15	10.5	1.4	3.5	0.0	0.0	0.0	0.0	0.0	0.0	15.4
16	10.6	-0.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0	14.7
17	10.5	-0.4	5.3	0.0	0.0	0.0	0.0	0.0	0.0	15.4
18	10.5	-0.7	6.4	0.0	0.0	0.0	0.0	0.0	0.0	16.3
19	10.5	-1.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	17.2
20	10.5	-1.2	9.2	0.0	0.0	0.0	0.0	0.0	0.0	18.4
21	10.4	-1.5	10.8	0.0	0.0	0.0	0.0	0.0	0.0	19.7
22	10.1	-1.8	0.0	9.3	18.5	0.0	0.0	0.0	0.0	26.9
23	10.1	-2.1	0.0	10.5	21.0	0.0	0.0	0.0	0.0	29.0
24	10.0	-1.9	0.0	11.7	23.5	0.0	0.0	0.0	0.0	31.6
25	9.9	-1.3	0.0	12.6	25.1	0.0	0.0	0.0	0.0	33.8
26	9.9	-0.7	0.0	13.1	26.2	0.0	0.0	0.0	0.0	35.4
27	9.9	-0.2	0.0	13.5	27.1	0.0	0.0	0.0	0.0	36.8
28	9.9	2.3	0.0	13.7	27.5	0.0	0.0	0.0	0.0	39.6
29	10.0	2.3	0.0	13.9	27.7	0.0	0.0	0.0	0.0	40.0
30	10.0	2.3	0.0	13.8	27.5	0.0	0.0	0.0	0.0	39.8
31	10.0	2.3	0.0	13.5	26.9	0.0	0.0	0.0	0.0	39.3
32	10.1	2.3	0.0	13.1	26.2	0.0	0.0	0.0	0.0	38.6
33	10.1	2.3	0.0	12.7	25.4	0.0	0.0	0.0	0.0	37.8
34	10.4	2.4	0.0	0.0	0.0	6.0	11.9	6.1	12.1	36.9
35	10.4	2.4	0.0	0.0	0.0	6.2	12.4	6.3	12.5	37.7
36	10.5	2.4	0.0	0.0	0.0	6.4	12.9	6.4	12.9	38.6
37	10.5	2.4	0.0	0.0	0.0	6.7	13.3	6.6	13.3	39.5
38	10.5	2.4	0.0	0.0	0.0	6.9	13.8	6.8	13.7	40.4
39	10.6	2.4	0.0	0.0	0.0	7.1	14.2	7.0	14.1	41.3
40	10.6	2.4	0.0	0.0	0.0	7.3	14.7	7.2	14.4	42.1
41	10.7	2.4	0.0	0.0	0.0	7.6	15.1	7.4	14.8	43.0
42	10.7	2.4	0.0	0.0	0.0	7.8	15.5	7.6	15.2	43.9
43	10.7	2.4	0.0	0.0	0.0	8.0	16.0	7.8	15.6	44.7
44	10.8	2.4	0.0	0.0	0.0	8.2	16.4	8.0	15.9	45.5
45	10.8	2.4	0.0	0.0	0.0	8.4	16.8	8.1	16.3	46.4
46	10.9	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.3
47	10.9	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.3
48	10.9	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4
49	11.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4
50	11.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.4
51	11.1	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.5
52	11.1	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.5
Annual Total	3800.9	468.8	408.6	1059.4	2118.9	605.7	1211.4	598.0	1195.9	9204.5

Table D.10 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a 2-tooth ewe with triplet ewe lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (triplet lambs)	ME m (per lamb)	ME m (triplet lambs)	ME g (per lamb)	ME g (triplet lambs)	Total MJME for ewe & lambs
1	10.3	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.7
2	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.7
3	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.8
4	10.4	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	11.9
5	10.4	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	12.0
6	10.4	1.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	12.1
7	10.4	1.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	12.3
8	10.5	1.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	12.5
9	10.5	1.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8
10	10.5	1.4	1.3	0.0	0.0	0.0	0.0	0.0	0.0	13.1
11	10.5	1.4	1.7	0.0	0.0	0.0	0.0	0.0	0.0	13.6
12	10.5	1.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	14.1
13	10.6	1.4	2.9	0.0	0.0	0.0	0.0	0.0	0.0	14.8
14	10.6	1.4	3.7	0.0	0.0	0.0	0.0	0.0	0.0	15.6
15	10.6	1.4	4.6	0.0	0.0	0.0	0.0	0.0	0.0	16.6
16	10.6	-0.2	5.7	0.0	0.0	0.0	0.0	0.0	0.0	16.2
17	10.6	-0.7	7.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0
18	10.6	-1.1	8.5	0.0	0.0	0.0	0.0	0.0	0.0	18.0
19	10.5	-1.6	10.2	0.0	0.0	0.0	0.0	0.0	0.0	19.2
20	10.5	-2.1	12.2	0.0	0.0	0.0	0.0	0.0	0.0	20.6
21	10.4	-2.5	14.4	0.0	0.0	0.0	0.0	0.0	0.0	22.2
22	10.1	-3.0	0.0	7.0	21.1	0.0	0.0	0.0	0.0	28.2
23	10.0	-3.5	0.0	8.0	23.9	0.0	0.0	0.0	0.0	30.4
24	9.9	-3.1	0.0	8.7	26.2	0.0	0.0	0.0	0.0	32.9
25	9.8	-2.2	0.0	9.3	27.9	0.0	0.0	0.0	0.0	35.5
26	9.7	-1.2	0.0	9.7	29.1	0.0	0.0	0.0	0.0	37.6
27	9.7	-0.3	0.0	10.0	30.0	0.0	0.0	0.0	0.0	39.3
28	9.7	2.9	0.0	10.1	30.3	0.0	0.0	0.0	0.0	42.9
29	9.7	2.9	0.0	10.2	30.5	0.0	0.0	0.0	0.0	43.2
30	9.8	2.9	0.0	10.0	30.0	0.0	0.0	0.0	0.0	42.7
31	9.8	2.9	0.0	9.8	29.3	0.0	0.0	0.0	0.0	42.1
32	9.9	2.9	0.0	9.5	28.5	0.0	0.0	0.0	0.0	41.3
33	9.9	2.9	0.0	9.2	27.5	0.0	0.0	0.0	0.0	40.4
34	10.2	3.1	0.0	0.0	0.0	4.4	13.1	5.0	15.1	41.6
35	10.3	3.1	0.0	0.0	0.0	4.6	13.7	5.2	15.6	42.7
36	10.4	3.1	0.0	0.0	0.0	4.7	14.2	5.4	16.1	43.8
37	10.4	3.1	0.0	0.0	0.0	4.9	14.8	5.5	16.6	44.9
38	10.5	3.1	0.0	0.0	0.0	5.1	15.3	5.7	17.1	46.0
39	10.5	3.1	0.0	0.0	0.0	5.3	15.8	5.9	17.6	47.1
40	10.6	3.1	0.0	0.0	0.0	5.5	16.4	6.1	18.2	48.1
41	10.6	3.1	0.0	0.0	0.0	5.6	16.9	6.2	18.7	49.2
42	10.7	3.1	0.0	0.0	0.0	5.8	17.4	6.4	19.2	50.3
43	10.7	3.1	0.0	0.0	0.0	6.0	17.9	6.6	19.7	51.4
44	10.8	3.1	0.0	0.0	0.0	6.1	18.4	6.7	20.2	52.4
45	10.8	3.1	0.0	0.0	0.0	6.3	18.9	6.9	20.6	53.5
46	10.9	3.1	0.0	0.0	0.0	6.5	19.4	7.0	21.1	54.5
47	10.9	3.1	0.0	0.0	0.0	6.6	19.9	7.2	21.5	55.5
48	11.0	3.1	0.0	0.0	0.0	6.8	20.4	7.3	21.9	56.4
49	11.0	3.1	0.0	0.0	0.0	7.0	20.9	7.4	22.3	57.4
50	11.1	3.1	0.0	0.0	0.0	7.1	21.4	7.6	22.7	58.3
51	11.1	3.1	0.0	0.0	0.0	3.1	9.3	3.3	9.9	33.4
52	11.2	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.3
Annual Total	3790.2	524.8	543.2	780.2	2340.6	710.1	2130.2	779.8	2339.3	11668.2

Table D.11 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a 2-tooth ewe with triplet ram lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (triplet lambs)	ME m (per lamb)	ME m (triplet lambs)	ME g (per lamb)	ME g (triplet lambs)	Total MJME for ewe & lambs
1	10.3	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.7
2	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.7
3	10.3	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	11.8
4	10.4	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	11.9
5	10.4	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	12.0
6	10.4	1.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	12.1
7	10.4	1.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	12.3
8	10.5	1.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	12.5
9	10.5	1.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8
10	10.5	1.4	1.3	0.0	0.0	0.0	0.0	0.0	0.0	13.1
11	10.5	1.4	1.7	0.0	0.0	0.0	0.0	0.0	0.0	13.6
12	10.5	1.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	14.1
13	10.6	1.4	2.9	0.0	0.0	0.0	0.0	0.0	0.0	14.8
14	10.6	1.4	3.7	0.0	0.0	0.0	0.0	0.0	0.0	15.6
15	10.6	1.4	4.6	0.0	0.0	0.0	0.0	0.0	0.0	16.6
16	10.6	-0.2	5.7	0.0	0.0	0.0	0.0	0.0	0.0	16.2
17	10.6	-0.7	7.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0
18	10.6	-1.1	8.5	0.0	0.0	0.0	0.0	0.0	0.0	18.0
19	10.5	-1.6	10.2	0.0	0.0	0.0	0.0	0.0	0.0	19.2
20	10.5	-2.1	12.2	0.0	0.0	0.0	0.0	0.0	0.0	20.6
21	10.4	-2.5	14.4	0.0	0.0	0.0	0.0	0.0	0.0	22.2
22	10.1	-3.0	0.0	8.0	23.9	0.0	0.0	0.0	0.0	30.9
23	10.0	-3.5	0.0	9.0	27.1	0.0	0.0	0.0	0.0	33.6
24	9.9	-3.1	0.0	9.9	29.7	0.0	0.0	0.0	0.0	36.4
25	9.8	-2.2	0.0	10.6	31.7	0.0	0.0	0.0	0.0	39.3
26	9.7	-1.2	0.0	11.0	33.1	0.0	0.0	0.0	0.0	41.6
27	9.7	-0.3	0.0	11.4	34.1	0.0	0.0	0.0	0.0	43.5
28	9.7	2.9	0.0	11.5	34.6	0.0	0.0	0.0	0.0	47.2
29	9.7	2.9	0.0	11.6	34.7	0.0	0.0	0.0	0.0	47.3
30	9.8	2.9	0.0	11.4	34.1	0.0	0.0	0.0	0.0	46.8
31	9.8	2.9	0.0	11.1	33.4	0.0	0.0	0.0	0.0	46.1
32	9.9	2.9	0.0	10.8	32.5	0.0	0.0	0.0	0.0	45.3
33	9.9	2.9	0.0	10.5	31.4	0.0	0.0	0.0	0.0	44.3
34	10.2	3.1	0.0	0.0	0.0	5.4	16.1	5.3	16.0	45.4
35	10.3	3.1	0.0	0.0	0.0	5.6	16.8	5.5	16.4	46.6
36	10.4	3.1	0.0	0.0	0.0	5.8	17.5	5.6	16.9	47.8
37	10.4	3.1	0.0	0.0	0.0	6.0	18.1	5.8	17.4	49.0
38	10.5	3.1	0.0	0.0	0.0	6.3	18.8	6.0	17.9	50.3
39	10.5	3.1	0.0	0.0	0.0	6.5	19.5	6.2	18.5	51.5
40	10.6	3.1	0.0	0.0	0.0	6.7	20.1	6.3	19.0	52.7
41	10.6	3.1	0.0	0.0	0.0	6.9	20.7	6.5	19.5	53.9
42	10.7	3.1	0.0	0.0	0.0	7.1	21.4	6.7	20.0	55.1
43	10.7	3.1	0.0	0.0	0.0	7.3	22.0	6.8	20.5	56.4
44	10.8	3.1	0.0	0.0	0.0	7.5	22.6	7.0	21.1	57.6
45	10.8	3.1	0.0	0.0	0.0	7.8	23.3	7.2	21.6	58.8
46	10.9	3.1	0.0	0.0	0.0	8.0	23.9	7.4	22.1	59.9
47	10.9	3.1	0.0	0.0	0.0	8.2	24.5	7.5	22.6	61.1
48	11.0	3.1	0.0	0.0	0.0	8.4	25.1	7.7	23.1	62.3
49	11.0	3.1	0.0	0.0	0.0	2.4	7.3	2.2	6.7	28.1
50	11.1	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.2
51	11.1	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.2
52	11.2	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.3
Annual Total	3790.2	524.8	543.2	887.0	2661.0	741.4	2224.1	698.4	2095.2	11838.5

Table D.12 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a MA ewe with a single ewe lamb

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (lamb)	ME m (lamb)	ME g (lamb)	Total MJME for ewe & lamb
1	10.5	0.0	0.0	0.0	0.0	0.0	10.5
2	10.5	0.0	0.0	0.0	0.0	0.0	10.6
3	10.5	0.0	0.1	0.0	0.0	0.0	10.6
4	10.5	0.0	0.1	0.0	0.0	0.0	10.6
5	10.5	0.0	0.1	0.0	0.0	0.0	10.6
6	10.5	0.0	0.2	0.0	0.0	0.0	10.7
7	10.5	0.0	0.2	0.0	0.0	0.0	10.8
8	10.5	0.0	0.3	0.0	0.0	0.0	10.8
9	10.5	0.0	0.4	0.0	0.0	0.0	11.0
10	10.5	0.0	0.6	0.0	0.0	0.0	11.1
11	10.5	0.0	0.8	0.0	0.0	0.0	11.3
12	10.5	0.0	1.0	0.0	0.0	0.0	11.6
13	10.5	0.0	1.4	0.0	0.0	0.0	11.9
14	10.5	0.0	1.7	0.0	0.0	0.0	12.2
15	10.5	0.0	2.2	0.0	0.0	0.0	12.7
16	10.5	0.0	2.7	0.0	0.0	0.0	13.2
17	10.5	0.0	3.3	0.0	0.0	0.0	13.8
18	10.5	0.0	4.0	0.0	0.0	0.0	14.5
19	10.5	0.0	4.8	0.0	0.0	0.0	15.3
20	10.5	0.0	5.7	0.0	0.0	0.0	16.2
21	10.5	0.0	6.8	0.0	0.0	0.0	17.3
22	10.3	0.0	0.0	10.7	0.0	0.0	21.0
23	10.3	0.0	0.0	12.2	0.0	0.0	22.5
24	10.3	0.0	0.0	13.6	0.0	0.0	23.9
25	10.3	0.0	0.0	14.9	0.0	0.0	25.1
26	10.3	0.0	0.0	15.6	0.0	0.0	25.9
27	10.3	0.0	0.0	16.2	0.0	0.0	26.5
28	10.3	0.0	0.0	16.5	0.0	0.0	26.8
29	10.3	0.0	0.0	16.7	0.0	0.0	27.0
30	10.3	0.0	0.0	16.7	0.0	0.0	27.0
31	10.3	0.0	0.0	16.7	0.0	0.0	26.9
32	10.3	0.0	0.0	16.4	0.0	0.0	26.7
33	10.3	0.0	0.0	15.9	0.0	0.0	26.2
34	10.5	0.0	0.0	0.0	5.8	7.7	24.0
35	10.5	0.0	0.0	0.0	6.0	7.9	24.4
36	10.5	0.0	0.0	0.0	6.2	8.1	24.8
37	10.5	0.0	0.0	0.0	6.4	8.3	25.2
38	10.5	0.0	0.0	0.0	6.6	8.5	25.7
39	10.5	0.0	0.0	0.0	6.8	8.7	26.0
40	10.5	0.0	0.0	0.0	7.0	8.9	26.4
41	10.5	0.0	0.0	0.0	7.2	9.1	26.8
42	10.5	0.0	0.0	0.0	1.0	1.3	12.9
43	10.5	0.0	0.0	0.0	0.0	0.0	10.5
44	10.5	0.0	0.0	0.0	0.0	0.0	10.5
45	10.5	0.0	0.0	0.0	0.0	0.0	10.5
46	10.5	0.0	0.0	0.0	0.0	0.0	10.5
47	10.5	0.0	0.0	0.0	0.0	0.0	10.5
48	10.5	0.0	0.0	0.0	0.0	0.0	10.5
49	10.5	0.0	0.0	0.0	0.0	0.0	10.5
50	10.5	0.0	0.0	0.0	0.0	0.0	10.5
51	10.5	0.0	0.0	0.0	0.0	0.0	10.5
52	10.5	0.0	0.0	0.0	0.0	0.0	10.5
Annual Total	3808.1	0.0	255.4	1274.9	371.1	480.2	6189.7

Table D.13 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a MA ewe with a single ram lamb

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (lamb)	ME m (lamb)	ME g (lamb)	Total MJME for ewe & lamb
1	10.5	0.0	0.0	0.0	0.0	0.0	10.5
2	10.5	0.0	0.0	0.0	0.0	0.0	10.6
3	10.5	0.0	0.1	0.0	0.0	0.0	10.6
4	10.5	0.0	0.1	0.0	0.0	0.0	10.6
5	10.5	0.0	0.1	0.0	0.0	0.0	10.6
6	10.5	0.0	0.2	0.0	0.0	0.0	10.7
7	10.5	0.0	0.2	0.0	0.0	0.0	10.8
8	10.5	0.0	0.3	0.0	0.0	0.0	10.8
9	10.5	0.0	0.4	0.0	0.0	0.0	11.0
10	10.5	0.0	0.6	0.0	0.0	0.0	11.1
11	10.5	0.0	0.8	0.0	0.0	0.0	11.3
12	10.5	0.0	1.0	0.0	0.0	0.0	11.6
13	10.5	0.0	1.4	0.0	0.0	0.0	11.9
14	10.5	0.0	1.7	0.0	0.0	0.0	12.2
15	10.5	0.0	2.2	0.0	0.0	0.0	12.7
16	10.5	0.0	2.7	0.0	0.0	0.0	13.2
17	10.5	0.0	3.3	0.0	0.0	0.0	13.8
18	10.5	0.0	4.0	0.0	0.0	0.0	14.5
19	10.5	0.0	4.8	0.0	0.0	0.0	15.3
20	10.5	0.0	5.7	0.0	0.0	0.0	16.2
21	10.5	0.0	6.8	0.0	0.0	0.0	17.3
22	10.3	0.0	0.0	12.1	0.0	0.0	22.4
23	10.3	0.0	0.0	13.7	0.0	0.0	24.0
24	10.3	0.0	0.0	15.4	0.0	0.0	25.6
25	10.3	0.0	0.0	16.7	0.0	0.0	27.0
26	10.3	0.0	0.0	17.5	0.0	0.0	27.8
27	10.3	0.0	0.0	18.2	0.0	0.0	28.4
28	10.3	0.0	0.0	18.5	0.0	0.0	28.8
29	10.3	0.0	0.0	18.8	0.0	0.0	29.0
30	10.3	0.0	0.0	18.8	0.0	0.0	29.1
31	10.3	0.0	0.0	18.7	0.0	0.0	29.0
32	10.3	0.0	0.0	18.4	0.0	0.0	28.7
33	10.3	0.0	0.0	17.9	0.0	0.0	28.2
34	10.5	0.0	0.0	0.0	7.1	8.0	25.6
35	10.5	0.0	0.0	0.0	7.4	8.3	26.1
36	10.5	0.0	0.0	0.0	7.6	8.5	26.6
37	10.5	0.0	0.0	0.0	7.9	8.7	27.1
38	10.5	0.0	0.0	0.0	8.1	9.0	27.6
39	10.5	0.0	0.0	0.0	8.4	9.2	28.1
40	10.5	0.0	0.0	0.0	2.4	2.7	15.6
41	10.5	0.0	0.0	0.0	0.0	0.0	10.5
42	10.5	0.0	0.0	0.0	0.0	0.0	10.5
43	10.5	0.0	0.0	0.0	0.0	0.0	10.5
44	10.5	0.0	0.0	0.0	0.0	0.0	10.5
45	10.5	0.0	0.0	0.0	0.0	0.0	10.5
46	10.5	0.0	0.0	0.0	0.0	0.0	10.5
47	10.5	0.0	0.0	0.0	0.0	0.0	10.5
48	10.5	0.0	0.0	0.0	0.0	0.0	10.5
49	10.5	0.0	0.0	0.0	0.0	0.0	10.5
50	10.5	0.0	0.0	0.0	0.0	0.0	10.5
51	10.5	0.0	0.0	0.0	0.0	0.0	10.5
52	10.5	0.0	0.0	0.0	0.0	0.0	10.5
Annual Total	3808.1	0.0	255.4	1432.7	342.2	380.4	6218.8

Table D.14 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a MA ewe with twin ewe lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (twin lambs)	ME m (per lamb)	ME m (twin lambs)	ME g (per lamb)	ME g (twin lambs)	Total MJME for ewe & lambs
1	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7
2	10.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.7
3	10.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.7
4	10.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.8
5	10.6	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.8
6	10.6	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	10.9
7	10.6	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	11.0
8	10.6	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	11.2
9	10.6	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	11.3
10	10.6	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
11	10.6	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	11.9
12	10.6	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	12.3
13	10.6	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	12.8
14	10.6	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	13.4
15	10.6	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	14.1
16	10.6	-0.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0	14.8
17	10.6	-0.4	5.3	0.0	0.0	0.0	0.0	0.0	0.0	15.5
18	10.6	-0.7	6.4	0.0	0.0	0.0	0.0	0.0	0.0	16.3
19	10.6	-1.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	17.3
20	10.5	-1.2	9.2	0.0	0.0	0.0	0.0	0.0	0.0	18.5
21	10.5	-1.5	10.8	0.0	0.0	0.0	0.0	0.0	0.0	19.8
22	10.2	-1.8	0.0	8.8	17.7	0.0	0.0	0.0	0.0	26.1
23	10.1	-2.1	0.0	10.0	20.1	0.0	0.0	0.0	0.0	28.1
24	10.1	-1.9	0.0	11.2	22.4	0.0	0.0	0.0	0.0	30.6
25	10.0	-1.3	0.0	12.0	24.0	0.0	0.0	0.0	0.0	32.8
26	10.0	-0.7	0.0	12.5	25.1	0.0	0.0	0.0	0.0	34.4
27	10.0	-0.2	0.0	13.0	25.9	0.0	0.0	0.0	0.0	35.7
28	10.0	0.9	0.0	13.2	26.3	0.0	0.0	0.0	0.0	37.3
29	10.0	0.9	0.0	13.3	26.6	0.0	0.0	0.0	0.0	37.6
30	10.0	0.9	0.0	13.3	26.6	0.0	0.0	0.0	0.0	37.5
31	10.0	0.9	0.0	13.0	26.0	0.0	0.0	0.0	0.0	37.0
32	10.1	0.9	0.0	12.6	25.3	0.0	0.0	0.0	0.0	36.3
33	10.1	0.9	0.0	12.2	24.5	0.0	0.0	0.0	0.0	35.5
34	10.3	0.9	0.0	0.0	0.0	5.1	10.2	6.4	12.7	34.2
35	10.3	0.9	0.0	0.0	0.0	5.3	10.6	6.6	13.1	35.0
36	10.4	0.9	0.0	0.0	0.0	5.5	11.0	6.8	13.6	35.9
37	10.4	0.9	0.0	0.0	0.0	5.7	11.4	7.0	14.0	36.7
38	10.4	0.9	0.0	0.0	0.0	5.9	11.8	7.2	14.4	37.5
39	10.4	0.9	0.0	0.0	0.0	6.1	12.1	7.4	14.8	38.3
40	10.4	0.9	0.0	0.0	0.0	6.3	12.5	7.6	15.2	39.0
41	10.4	0.9	0.0	0.0	0.0	6.4	12.9	7.8	15.5	39.8
42	10.5	0.9	0.0	0.0	0.0	6.6	13.2	7.9	15.9	40.6
43	10.5	0.9	0.0	0.0	0.0	6.8	13.6	8.1	16.2	41.3
44	10.5	0.9	0.0	0.0	0.0	7.0	14.0	8.3	16.6	42.0
45	10.5	0.9	0.0	0.0	0.0	7.2	14.3	8.4	16.9	42.7
46	10.5	0.9	0.0	0.0	0.0	2.1	4.2	2.4	4.9	20.5
47	10.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
48	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
49	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
50	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
51	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
52	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
Annual Total	3797.9	75.0	408.6	1016.6	2033.3	531.3	1062.6	643.1	1286.3	8663.6

Table D.15 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a MA ewe with twin ram lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (twin lambs)	ME m (per lamb)	ME m (twin lambs)	ME g (per lamb)	ME g (twin lambs)	Total MJME for ewe & lambs
1	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7
2	10.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.7
3	10.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.7
4	10.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.8
5	10.6	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.8
6	10.6	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	10.9
7	10.6	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	11.0
8	10.6	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	11.2
9	10.6	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	11.3
10	10.6	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
11	10.6	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	11.9
12	10.6	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	12.3
13	10.6	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	12.8
14	10.6	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	13.4
15	10.6	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	14.1
16	10.6	-0.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0	14.8
17	10.6	-0.4	5.3	0.0	0.0	0.0	0.0	0.0	0.0	15.5
18	10.6	-0.7	6.4	0.0	0.0	0.0	0.0	0.0	0.0	16.3
19	10.6	-1.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	17.3
20	10.5	-1.2	9.2	0.0	0.0	0.0	0.0	0.0	0.0	18.5
21	10.5	-1.5	10.8	0.0	0.0	0.0	0.0	0.0	0.0	19.8
22	10.2	-1.8	0.0	9.9	19.9	0.0	0.0	0.0	0.0	28.3
23	10.1	-2.1	0.0	11.3	22.6	0.0	0.0	0.0	0.0	30.7
24	10.1	-1.9	0.0	12.6	25.3	0.0	0.0	0.0	0.0	33.5
25	10.0	-1.3	0.0	13.5	27.1	0.0	0.0	0.0	0.0	35.8
26	10.0	-0.7	0.0	14.2	28.3	0.0	0.0	0.0	0.0	37.6
27	10.0	-0.2	0.0	14.6	29.2	0.0	0.0	0.0	0.0	39.1
28	10.0	0.9	0.0	14.8	29.7	0.0	0.0	0.0	0.0	40.6
29	10.0	0.9	0.0	15.0	30.0	0.0	0.0	0.0	0.0	41.0
30	10.0	0.9	0.0	14.9	29.8	0.0	0.0	0.0	0.0	40.8
31	10.0	0.9	0.0	14.6	29.2	0.0	0.0	0.0	0.0	40.2
32	10.1	0.9	0.0	14.2	28.5	0.0	0.0	0.0	0.0	39.5
33	10.1	0.9	0.0	13.8	27.6	0.0	0.0	0.0	0.0	38.6
34	10.3	0.9	0.0	0.0	0.0	6.3	12.5	6.7	13.3	37.1
35	10.3	0.9	0.0	0.0	0.0	6.5	13.0	6.9	13.7	38.0
36	10.4	0.9	0.0	0.0	0.0	6.7	13.5	7.1	14.2	38.9
37	10.4	0.9	0.0	0.0	0.0	7.0	14.0	7.3	14.6	39.9
38	10.4	0.9	0.0	0.0	0.0	7.2	14.4	7.5	15.0	40.8
39	10.4	0.9	0.0	0.0	0.0	7.4	14.9	7.7	15.4	41.7
40	10.4	0.9	0.0	0.0	0.0	7.7	15.4	7.9	15.9	42.6
41	10.4	0.9	0.0	0.0	0.0	7.9	15.8	8.1	16.3	43.5
42	10.5	0.9	0.0	0.0	0.0	8.1	16.3	8.3	16.7	44.4
43	10.5	0.9	0.0	0.0	0.0	8.4	16.7	8.5	17.1	45.2
44	10.5	0.9	0.0	0.0	0.0	2.4	4.9	2.5	5.0	21.2
45	10.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
46	10.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
47	10.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
48	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
49	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
50	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
51	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
52	10.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
Annual Total	3797.9	75.0	408.6	1145.4	2290.8	529.5	1058.9	549.9	1099.8	8731.0

Table D.16 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a MA ewe with triplet ewe lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (triplet lambs)	ME m (per lamb)	ME m (triplet lambs)	ME g (per lamb)	ME g (triplet lambs)	Total MJME for ewe & lambs
1	10.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7
2	10.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.8
3	10.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.8
4	10.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.9
5	10.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.9
6	10.7	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	11.1
7	10.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	11.2
8	10.7	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	11.4
9	10.7	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	11.7
10	10.7	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	12.0
11	10.7	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	12.4
12	10.7	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	12.9
13	10.7	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	13.6
14	10.7	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	14.4
15	10.7	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	15.3
16	10.7	-0.2	5.7	0.0	0.0	0.0	0.0	0.0	0.0	16.2
17	10.7	-0.7	7.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0
18	10.7	-1.1	8.5	0.0	0.0	0.0	0.0	0.0	0.0	18.1
19	10.6	-1.6	10.2	0.0	0.0	0.0	0.0	0.0	0.0	19.3
20	10.6	-2.1	12.2	0.0	0.0	0.0	0.0	0.0	0.0	20.7
21	10.5	-2.5	14.4	0.0	0.0	0.0	0.0	0.0	0.0	22.3
22	10.1	-3.0	0.0	7.5	22.6	0.0	0.0	0.0	0.0	29.8
23	10.0	-3.5	0.0	8.5	25.6	0.0	0.0	0.0	0.0	32.2
24	9.9	-3.1	0.0	9.4	28.2	0.0	0.0	0.0	0.0	35.0
25	9.9	-2.2	0.0	10.0	30.1	0.0	0.0	0.0	0.0	37.8
26	9.8	-1.2	0.0	10.5	31.4	0.0	0.0	0.0	0.0	40.0
27	9.8	-0.3	0.0	10.8	32.4	0.0	0.0	0.0	0.0	41.8
28	9.8	1.6	0.0	10.9	32.8	0.0	0.0	0.0	0.0	44.2
29	9.8	1.6	0.0	11.0	33.1	0.0	0.0	0.0	0.0	44.5
30	9.8	1.6	0.0	10.8	32.5	0.0	0.0	0.0	0.0	43.9
31	9.9	1.6	0.0	10.6	31.8	0.0	0.0	0.0	0.0	43.3
32	9.9	1.6	0.0	10.3	30.9	0.0	0.0	0.0	0.0	42.4
33	9.9	1.6	0.0	10.0	29.9	0.0	0.0	0.0	0.0	41.4
34	10.2	1.6	0.0	0.0	0.0	4.6	13.8	5.5	16.6	42.1
35	10.2	1.6	0.0	0.0	0.0	4.8	14.3	5.7	17.1	43.3
36	10.3	1.6	0.0	0.0	0.0	5.0	14.9	5.9	17.7	44.4
37	10.3	1.6	0.0	0.0	0.0	5.2	15.5	6.1	18.2	45.6
38	10.3	1.6	0.0	0.0	0.0	5.3	16.0	6.3	18.8	46.7
39	10.3	1.6	0.0	0.0	0.0	5.5	16.6	6.5	19.4	47.9
40	10.4	1.6	0.0	0.0	0.0	5.7	17.1	6.6	19.9	49.0
41	10.4	1.6	0.0	0.0	0.0	5.9	17.7	6.8	20.5	50.1
42	10.4	1.6	0.0	0.0	0.0	6.1	18.2	7.0	21.0	51.2
43	10.4	1.6	0.0	0.0	0.0	6.2	18.7	7.2	21.6	52.3
44	10.5	1.6	0.0	0.0	0.0	6.4	19.3	7.4	22.1	53.4
45	10.5	1.6	0.0	0.0	0.0	6.6	19.8	7.5	22.6	54.4
46	10.5	1.6	0.0	0.0	0.0	6.8	20.3	7.7	23.0	55.4
47	10.6	1.6	0.0	0.0	0.0	6.9	20.8	7.8	23.5	56.4
48	10.6	1.6	0.0	0.0	0.0	7.1	21.4	8.0	23.9	57.4
49	10.6	1.6	0.0	0.0	0.0	4.1	12.4	4.6	13.8	38.5
50	10.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
51	10.7	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
52	10.7	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.3
Annual Total	3790.4	125.0	543.2	843.0	2529.0	645.9	1937.6	745.9	2237.7	11162.8

Table D.17 Weekly energy requirements (MJME/hd/day) for maintenance (ME m), liveweight gain (ME g), pregnancy (ME p), and lactation (ME l) of a MA ewe with triplet ram lambs

Week starting from ewe mating date	ME m (ewe)	ME g (ewe)	ME p (ewe)	ME l (per lamb)	ME l (triplet lambs)	ME m (per lamb)	ME m (triplet lambs)	ME g (per lamb)	ME g (triplet lambs)	Total MJME for ewe & lambs
1	10.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7
2	10.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.8
3	10.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	10.8
4	10.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.9
5	10.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	10.9
6	10.7	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	11.1
7	10.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	11.2
8	10.7	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	11.4
9	10.7	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	11.7
10	10.7	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	12.0
11	10.7	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	12.4
12	10.7	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	12.9
13	10.7	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	13.6
14	10.7	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	14.4
15	10.7	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	15.3
16	10.7	-0.2	5.7	0.0	0.0	0.0	0.0	0.0	0.0	16.2
17	10.7	-0.7	7.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0
18	10.7	-1.1	8.5	0.0	0.0	0.0	0.0	0.0	0.0	18.1
19	10.6	-1.6	10.2	0.0	0.0	0.0	0.0	0.0	0.0	19.3
20	10.6	-2.1	12.2	0.0	0.0	0.0	0.0	0.0	0.0	20.7
21	10.5	-2.5	14.4	0.0	0.0	0.0	0.0	0.0	0.0	22.3
22	10.1	-3.0	0.0	8.5	25.5	0.0	0.0	0.0	0.0	32.7
23	10.0	-3.5	0.0	9.7	29.0	0.0	0.0	0.0	0.0	35.6
24	9.9	-3.1	0.0	10.6	31.9	0.0	0.0	0.0	0.0	38.7
25	9.9	-2.2	0.0	11.4	34.1	0.0	0.0	0.0	0.0	41.8
26	9.8	-1.2	0.0	11.9	35.6	0.0	0.0	0.0	0.0	44.2
27	9.8	-0.3	0.0	12.3	36.8	0.0	0.0	0.0	0.0	46.2
28	9.8	1.6	0.0	12.4	37.3	0.0	0.0	0.0	0.0	48.7
29	9.8	1.6	0.0	12.5	37.4	0.0	0.0	0.0	0.0	48.8
30	9.8	1.6	0.0	12.3	36.9	0.0	0.0	0.0	0.0	48.3
31	9.9	1.6	0.0	12.0	36.1	0.0	0.0	0.0	0.0	47.5
32	9.9	1.6	0.0	11.7	35.1	0.0	0.0	0.0	0.0	46.6
33	9.9	1.6	0.0	11.3	34.0	0.0	0.0	0.0	0.0	45.5
34	10.2	1.6	0.0	0.0	0.0	5.6	16.9	5.8	17.4	46.1
35	10.2	1.6	0.0	0.0	0.0	5.9	17.6	6.0	18.0	47.4
36	10.3	1.6	0.0	0.0	0.0	6.1	18.3	6.2	18.5	48.7
37	10.3	1.6	0.0	0.0	0.0	6.3	19.0	6.4	19.1	50.0
38	10.3	1.6	0.0	0.0	0.0	6.6	19.7	6.6	19.7	51.2
39	10.3	1.6	0.0	0.0	0.0	6.8	20.4	6.7	20.2	52.5
40	10.4	1.6	0.0	0.0	0.0	7.0	21.0	6.9	20.8	53.8
41	10.4	1.6	0.0	0.0	0.0	7.2	21.7	7.1	21.4	55.1
42	10.4	1.6	0.0	0.0	0.0	7.5	22.4	7.3	22.0	56.3
43	10.4	1.6	0.0	0.0	0.0	7.7	23.0	7.5	22.6	57.6
44	10.5	1.6	0.0	0.0	0.0	7.9	23.7	7.7	23.1	58.9
45	10.5	1.6	0.0	0.0	0.0	8.1	24.3	7.9	23.7	60.1
46	10.5	1.6	0.0	0.0	0.0	8.3	25.0	8.1	24.2	61.3
47	10.6	1.6	0.0	0.0	0.0	3.6	10.9	3.5	10.5	33.6
48	10.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
49	10.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
50	10.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
51	10.7	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2
52	10.7	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.3
Annual Total	3790.4	125.0	543.2	956.0	2868.1	662.4	1987.3	656.4	1969.3	11283.3

Table D.18 Summary of the combined total annual energy requirement (MJME) of breeding females and their lambs

Dam	Litter size & sex of lamb(s)						
	unmated	Single		Twin		Triplet	
		ewe lamb	ram lamb	ewe lamb	ram lamb	ewe lamb	ram lamb
Hogget	4,256	6,605	6,648	9,098	9,178	-	-
2-tooth ewe	-	6,610	6,638	9,138	9,204	11,668	11,839
MA ewe	-	6,190	6,219	8,664	8,731	11,163	11,283

Appendix E

Average SFF South Island Schedule Prices (2010-14)

Table E.1 Average (2010-2014) Silver Fern Farms South Island schedule price ($/kg) by week of year for Y, P and T grade lambs of different weight ranges

Week of year	9.1<13.3kg	13.3<14kg	14<16kg	16<19kg	19<22kg	22<23kg	23<25kg	25<30kg	30kg+
1	2.92	4.02	5.12	5.12	5.12	5.12	4.41	3.42	2.67
2	2.86	3.96	5.06	5.06	5.06	5.06	4.35	3.36	2.61
3	2.83	3.93	5.03	5.03	5.03	5.03	4.32	3.33	2.58
4	2.79	3.89	4.99	4.99	4.99	4.99	4.28	3.29	2.54
5	2.77	3.87	5.01	5.05	5.05	5.01	4.26	3.35	2.60
6	2.68	3.78	4.92	4.96	4.96	4.92	4.17	3.26	2.51
7	2.62	3.72	4.86	4.92	4.92	4.86	4.11	3.22	2.47
8	2.55	3.65	4.82	4.88	4.88	4.82	4.04	3.18	2.43
9	2.53	3.63	4.78	4.84	4.84	4.78	4.02	3.14	2.39
10	2.51	3.61	4.78	4.78	4.78	4.78	4.00	3.08	2.33
11	2.51	3.61	4.78	4.78	4.78	4.78	4.00	3.08	2.33
12	2.51	3.61	4.78	4.78	4.78	4.78	4.00	3.08	2.33
13	2.47	3.57	4.74	4.74	4.74	4.74	3.96	3.04	2.29
14	2.47	3.57	4.74	4.74	4.74	4.74	3.96	3.04	2.29
15	2.51	3.61	4.78	4.78	4.78	4.78	4.00	3.08	2.33
16	2.54	3.64	4.81	4.81	4.81	4.81	4.03	3.11	2.36
17	2.57	3.67	4.84	4.84	4.84	4.84	4.06	3.14	2.39
18	2.57	3.67	4.84	4.84	4.84	4.84	4.06	3.14	2.39
19	2.63	3.73	4.90	4.90	4.90	4.90	4.12	3.20	2.45
20	2.74	3.84	5.01	5.01	5.01	4.99	4.23	3.31	2.56
21	2.76	3.86	5.03	5.03	5.03	5.01	4.25	3.33	2.58
22	2.83	3.93	5.10	5.10	5.10	5.08	4.32	3.40	2.65
23	2.85	3.95	5.12	5.12	5.12	5.10	4.34	3.42	2.67
24	2.92	4.02	5.19	5.19	5.19	5.17	4.41	3.49	2.74
25	2.98	4.06	5.25	5.25	5.25	5.23	4.47	3.55	2.80
26	3.02	4.12	5.29	5.29	5.29	5.27	4.51	3.59	2.84
27	3.06	4.16	5.33	5.33	5.33	5.31	4.55	3.63	2.88
28	3.08	4.18	5.35	5.35	5.35	5.33	4.57	3.65	2.90
29	3.10	4.20	5.37	5.37	5.37	5.35	4.59	3.67	2.92
30	3.02	4.14	5.29	5.29	5.29	5.27	4.51	3.59	2.84
31	3.06	4.16	5.33	5.33	5.33	5.31	4.55	3.63	2.88
32	3.10	4.20	5.37	5.37	5.37	5.35	4.59	3.67	2.92
33	3.10	4.20	5.37	5.37	5.37	5.35	4.59	3.67	2.92
34	3.13	4.23	5.40	5.40	5.40	5.38	4.62	3.70	2.95
35	3.16	4.26	5.43	5.43	5.43	5.41	4.65	3.73	2.98
36	3.22	4.32	5.49	5.49	5.49	5.47	4.71	3.79	3.04
37	3.30	4.40	5.57	5.57	5.57	5.57	4.77	3.87	3.12
38	3.31	4.41	5.58	5.58	5.58	5.58	4.78	3.88	3.13
39	3.36	4.46	5.63	5.63	5.63	5.63	4.90	3.93	3.18
40	3.36	4.46	5.63	5.63	5.63	5.63	4.90	3.93	3.18
41	3.40	4.50	5.67	5.67	5.67	5.67	4.94	3.97	3.22
42	3.42	4.52	5.69	5.69	5.69	5.69	4.96	3.99	3.24
43	3.44	4.54	5.71	5.71	5.71	5.71	4.98	4.01	3.26
44	3.57	4.67	5.84	5.84	5.84	5.84	5.11	4.14	3.39
45	3.59	4.69	5.86	5.86	5.86	5.86	5.13	4.16	3.41
46	3.54	4.64	5.81	5.81	5.81	5.81	5.08	4.11	3.36
47	3.48	4.58	5.75	5.75	5.75	5.75	5.16	4.05	3.30
48	3.37	4.47	5.64	5.64	5.64	5.64	5.05	3.94	3.19
49	3.30	4.40	5.57	5.57	5.57	5.57	4.80	3.87	3.12
50	3.14	4.24	5.43	5.43	5.43	5.43	4.64	3.73	2.98
51	3.05	4.15	5.34	5.34	5.34	5.34	4.55	3.64	2.89
52	2.98	4.08	5.27	5.27	5.27	5.27	4.48	3.57	2.82

Table E.2 Average (2010-2014) Silver Fern Farms South Island schedule price ($/kg) by week of year for F grade lambs of different weight ranges

Week of year	9.1<13.3kg	13.3<14kg	14<16kg	16<19kg	19<22kg	22<23kg	23<29kg	25<30kg	30kg+
1	2.44	3.54	5.00	5.00	5.00	5.00	4.05	3.30	2.55
2	2.38	3.48	4.94	4.94	4.94	4.94	3.99	3.24	2.49
3	2.35	3.45	4.91	4.91	4.91	4.91	3.96	3.21	2.46
4	2.33	3.43	4.89	4.89	4.89	4.89	3.94	3.19	2.44
5	2.29	3.39	4.85	4.89	4.89	4.89	3.78	3.19	2.44
6	2.39	3.46	4.76	4.80	4.80	4.80	3.69	3.10	2.35
7	2.33	3.40	4.70	4.76	4.76	4.76	3.94	3.06	2.31
8	2.30	3.37	4.70	4.76	4.76	4.76	3.91	3.06	2.31
9	2.09	3.18	4.70	4.76	4.76	4.76	3.89	3.06	2.31
10	2.07	3.16	4.70	4.70	4.70	4.70	3.85	3.00	2.25
11	2.07	3.16	4.70	4.70	4.70	4.70	3.85	3.00	2.25
12	2.04	3.13	4.67	4.67	4.67	4.67	3.82	2.97	2.22
13	2.03	3.13	4.66	4.66	4.66	4.66	3.81	2.96	2.21
14	2.03	3.13	4.66	4.66	4.66	4.66	3.81	2.96	2.21
15	2.07	3.17	4.70	4.70	4.70	4.70	3.85	3.00	2.25
16	2.10	3.20	4.73	4.73	4.73	4.73	3.88	3.03	2.28
17	2.11	3.21	4.74	4.74	4.74	4.74	3.89	3.04	2.29
18	2.11	3.21	4.74	4.74	4.74	4.74	3.89	3.04	2.29
19	2.15	3.25	4.78	4.78	4.78	4.78	3.93	3.08	2.33
20	2.26	3.36	4.89	4.89	4.87	4.87	4.04	3.19	2.44
21	2.28	3.38	4.91	4.91	4.89	4.89	4.06	3.21	2.46
22	2.39	3.49	5.02	5.02	5.00	5.00	4.17	3.32	2.57
23	2.41	3.51	5.04	5.04	5.02	5.02	4.21	3.34	2.59
24	2.44	3.58	5.11	5.11	5.09	5.09	4.26	3.41	2.66
25	2.50	3.64	5.17	5.17	5.15	5.15	4.32	3.47	2.72
26	2.54	3.68	5.21	5.21	5.21	5.07	4.36	3.51	2.76
27	2.62	3.72	5.25	5.25	5.25	5.11	4.40	3.55	2.80
28	2.62	3.74	5.27	5.27	5.27	5.13	4.42	3.57	2.82
29	2.64	3.74	5.27	5.27	5.27	5.13	4.42	3.57	2.82
30	2.64	3.74	5.27	5.27	5.27	5.13	4.42	3.57	2.82
31	2.62	3.72	5.25	5.25	5.25	5.23	4.38	3.55	2.80
32	2.66	3.76	5.29	5.29	5.29	5.27	4.42	3.59	2.84
33	2.69	3.79	5.32	5.32	5.32	5.30	4.45	3.62	2.87
34	2.69	3.79	5.32	5.32	5.32	5.30	4.45	3.62	2.87
35	2.76	3.86	5.39	5.39	5.39	5.37	4.52	3.69	2.94
36	2.78	3.88	5.41	5.41	5.41	5.39	4.54	3.71	2.96
37	2.86	3.96	5.49	5.49	5.49	5.49	4.60	3.79	3.04
38	2.87	3.97	5.50	5.50	5.50	5.50	4.61	3.80	3.05
39	2.92	4.02	5.55	5.55	5.55	5.55	4.68	3.85	3.10
40	2.94	4.04	5.57	5.57	5.57	5.57	4.70	3.87	3.12
41	2.94	4.04	5.57	5.57	5.57	5.57	4.70	3.87	3.12
42	2.94	4.04	5.57	5.57	5.57	5.57	4.70	3.87	3.12
43	3.00	4.10	5.63	5.63	5.63	5.63	4.76	3.93	3.18
44	3.02	4.12	5.65	5.65	5.65	5.65	4.78	3.95	3.20
45	3.19	4.29	5.58	5.58	5.58	5.58	4.83	3.88	3.13
46	3.14	4.24	5.65	5.65	5.65	5.65	4.90	3.95	3.20
47	3.08	4.18	5.59	5.59	5.59	5.59	4.98	3.89	3.14
48	2.97	4.07	5.48	5.48	5.48	5.48	4.87	3.78	3.03
49	2.90	4.00	5.41	5.41	5.41	5.41	4.74	3.71	2.96
50	2.74	3.84	5.27	5.27	5.27	5.27	4.60	3.57	2.82
51	2.65	3.75	5.18	5.18	5.18	5.18	4.51	3.48	2.73
52	2.62	3.72	5.15	5.15	5.15	5.15	4.48	3.45	2.70

Table E.3 Average (2010-2014) Silver Fern Farms South Island schedule price ($/kg) by week of year for Mutton of different grade and weight ranges

Week of year	MX,ML			MH,MP	MM,MF
	<17kg	17<23.2kg	23.2kg+		
1	3.10	3.10	3.10	2.38	2.18
2	3.08	3.08	3.08	2.36	2.16
3	3.06	3.06	3.06	2.34	2.14
4	3.09	3.09	3.09	2.37	2.17
5	3.05	3.05	3.05	2.33	2.13
6	3.01	3.01	3.01	2.29	2.09
7	3.01	3.01	3.01	2.29	2.09
8	2.98	2.98	2.98	2.24	2.02
9	2.99	2.99	2.99	2.27	2.03
10	2.97	2.97	2.97	2.25	2.01
11	2.94	2.94	2.94	2.22	2.02
12	2.94	2.94	2.94	2.22	2.02
13	2.92	2.92	2.92	2.20	2.00
14	2.92	2.92	2.92	2.20	2.00
15	2.89	2.89	2.89	2.17	1.97
16	2.89	2.89	2.89	2.17	1.97
17	2.89	2.89	2.89	2.17	1.97
18	2.91	2.91	2.91	2.19	1.99
19	2.91	2.91	2.91	2.19	1.99
20	2.91	2.91	2.91	2.19	1.99
21	2.93	2.93	2.93	2.21	2.01
22	2.97	2.97	2.97	2.25	2.05
23	2.99	2.99	2.99	2.27	2.07
24	3.03	3.03	3.03	2.31	2.11
25	3.06	3.06	3.06	2.34	2.14
26	3.08	3.08	3.08	2.36	2.16
27	3.08	3.08	3.08	2.36	2.16
28	3.10	3.10	3.10	2.38	2.18
29	3.10	3.10	3.10	2.38	2.18
30	3.10	3.10	3.10	2.38	2.18
31	3.10	3.10	3.10	2.38	2.18
32	3.08	3.08	3.08	2.36	2.16
33	3.04	3.04	3.04	2.32	2.12
34	3.06	3.06	3.06	2.34	2.14
35	3.06	3.06	3.06	2.34	2.14
36	3.06	3.06	3.06	2.34	2.14
37	3.06	3.06	3.06	2.34	2.14
38	3.06	3.06	3.06	2.34	2.14
39	3.05	3.05	3.05	2.33	2.13
40	3.10	3.10	3.10	2.38	2.18
41	3.13	3.13	3.13	2.41	2.21
42	3.16	3.16	3.16	2.44	2.24
43	3.16	3.16	3.16	2.44	2.24
44	3.22	3.22	3.22	2.50	2.30
45	3.38	3.38	3.38	2.62	2.42
46	3.44	3.44	3.44	2.64	2.44
47	3.50	3.50	3.50	2.70	2.50
48	3.49	3.49	3.49	2.69	2.49
49	3.47	3.47	3.47	2.67	2.47
50	3.37	3.37	3.37	2.57	2.37
51	3.32	3.32	3.32	2.52	2.32
52	3.28	3.28	3.28	2.48	2.28

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